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TACTICAL FORWARD AREA SURVEILLANCE AND CONTROL INTERNETTING STUDY
Final Report, Volume I, Summary

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A tactical air surveillance and control system concept for tracking large numbers of aircraft, many of which are highly maneuverable and capable of flying at low altitudes, is analyzed. The survivable, automated, non-hierarchically netted system investigated provides continuous, non-redundant System Tracks for tactical air control.

Nine alternative netted system configurations are defined and analyzed. These differ by radar mode (track-while-scan or computer-directed-track), (Continued)

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track file structure and location, and whether or not all radars or only selected ones are used to track each aircraft. Flow charts, and communications and data processing requirements are developed for each configuration. Some versions are simulated in the TACRAN (Tactical Air Control Radar Net) distributed system simulation developed during the study.

The real-time data processing functions required by such a system are investigated, with emphasis on track initiation, association, and filtering. Parametric analyses of algorithms for these functions provide measures of their performance under a variety of conditions and also determine the accuracy and rates required of the radar measurements.

The results demonstrate that the system concept is feasible with reasonable radar, communications, and data processing requirements.

ABSTRACT

A tactical air surveillance and control system concept for tracking large numbers of aircraft, many of which are highly maneuverable and capable of flying at low altitudes, is analyzed. The survivable, automated, non-hierarchically netted system investigated provides continuous, non-redundant System Tracks for tactical air control.

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The results demonstrate that the system concept is feasible with reasonable radar, communications, and data processing requirements.

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1 EXECUTIVE SUMMARY

1.1 BACKGROUND

A tactical air surveillance and control system concept that has potential for operating in the complex tactical air environment anticipated in the next few decades is being developed by the Air Force Systems Command's Electronic Systems Division (ESD/XRT) and the MITRE Corporation. This new approach to tactical air surveillance, evolved in response to anticipated operational requirements, including the following:

Track Low-Flying Aircraft. To be able to track low-flying (100 m altitude) aircraft a surveillance system must cover the area of interest with closely spaced radars. The spacing of these radars depends primarily on the local terrain, but 30 km is typical.

Track Large Numbers of Aircraft. To be able to handle a large number of aircraft (typical numbers used in the study were 1,000 aircraft over a 20,000 n mi^2 area), the surveillance system cannot rely on manual tracking and must be essentially entirely automated.

Provide Continuous Non-Redundant Tracks. To be able to provide continuous, non-redundant tracks for use in tactical air control operations, aircraft identification and fratricide prevention, the system must be able to reliably combine information from any available sensors. Non-redundant tracks are also needed to avoid confusion in using the data and to conserve data processing and communications resources. To achieve continuous tracks on low-flying aircraft requires combining short segments of track from different radars. For high-altitude aircraft, which can be seen by many radars because of overlapping coverage, multiple tracks on each aircraft must be prevented or eliminated by appropriate processing.

At all altitudes there is a need to fill in radar gaps caused by electronic countermeasures, terrain masking, and radar attrition. Meeting the anticipated requirement for continuous non-redundant tracks on all aircraft requires cooperation among the radars, and this leads to a system of netted radars with overlapping coverage.

System Survivability. The need for a survivable system, even with the loss of individual radars and communications links, calls for a redundant system with no unique critical elements. This favors decentralized operation and non-hierarchical netting. However, system design should not constrain the organizational structure. In addition, it must be tolerant to selective intermittent shutdown or loss of radars and communications links, due to frequent movement of elements, antiradiation missiles, or other causes of attrition, without serious loss of system effectiveness.

* * *

To construct a workable, survivable, netted system that can provide continuous, non-redundant tracks on large numbers of aircraft, many with the capability of executing very high-g maneuvers (5g-10g), will require a careful system design with a level of automation sophistication that goes well beyond simply automating the same functions now performed manually. In the air surveillance system concept investigated (depicted in Fig. 1.1), many highly mobile radars are internetted with an average spacing of about 30 km to provide low-altitude coverage and line-of-sight communications. The maximum range of the radars (80-90 km) is sufficient to provide considerable overlapping coverage; as many as 25 radars can see each aircraft (except those at very low altitudes). To the extent possible, each radar site is connected to its three or four nearest neighbors in a non-hierarchical network. Air operations are planned and executed at a second type of site, termed an Operations Facility.

Figure 1.1. Internetted Tactical Air Surveillance System

The redundant communications and radar coverage achieved offer the potential in a well-designed system to greatly enhance system survivability, to provide improved surveillance and tracking capabilities, and to improve the system's performance against electronic countermeasures.

1.2 STUDY OBJECTIVE AND SCOPE

The objective of the study described in this report, as given in the Statement of Work, was "to determine the functional and data processing requirements for improving certain elements such as track initiation, tracking, track correlation and message processing, related to future tactical forward area surveillance concepts."

The specific study tasks can be summarized as follows:

1. Define and analyze alternative system configurations to determine tradeoffs, with emphasis on the different possible

locations for performing the various tracking functions. Define the data processing and communications loads for each configuration. [Tasks 3, 4][1]

2. Describe the real-time data processing functions to be performed, and recommend solutions to any problem areas. Functions to be considered in detail include track initiation, association (correlation) of measurements with tracks, association of tracks with tracks, and track filtering. [Task 1]

3. Define requirements on the information that must be provided by the radars to support an automated netted surveillance system. [Task 2]

One area that was not included in the study, but which could have a profound effect on the system design, is the system's responses to electronic countermeasures and anti-radiation missiles that might result from redundancy and internetting. The problem of the registration of the radars was also not investigated.

1.3 SUMMARY OF RESULTS AND ACCOMPLISHMENTS

The basic purpose of the study was to illuminate certain areas of concern about automated netted surveillance systems. Thus the basic results of the study are the technical details which are described in Vol. 2 of this report and summarized in this volume. A few general statements of the findings of the study are given below; these are followed by a brief summary of the technical accomplishments and results.

1.3.1 Principal Findings

1. The study results demonstrate that an automated, internetted tactical air surveillance system is feasible, and that it can be used to combine multiple sensor information into continuous, non-redundant tracks with reasonable radar, communications, and data processing requirements.

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[1] Original task numbers.

For example, a 70-radar network tracking 1,000 aircraft requires 40-kilobit-per-second communication links and one million-instruction-per-second (MIPS) data processors.

2. Automatic tracking of large numbers of aircraft is reasonable using today's data processing technology.

3. An analysis of radar data requirements shows that the automated netted system concept imposes no new requirements on radars--that is, no requirements in addition to those that already exist for surveillance radars.

4. Highly maneuvering aircraft (5g-10g) require an effective radar measurement interval of from 1 to 3 seconds. The study showed how this can be achieved by netting track-while-scan radars having much longer scan periods.

5. Solutions to most of the critical algorithm problems of an automated netted system were shown to exist, and their effectiveness was demonstrated by computer simulation during the study. The principal critical functions investigated include track initiation, association of measurements with tracks, and track filtering.

1.3.2 Technical Accomplishments and Results

The basic output of the tactical air surveillance system considered in this study is a file of System Tracks maintained in computer memory and used by the Operations Facilities. These System Tracks are representations of the flight paths of all aircraft in the surveillance region. Many or all sites in the system may have a copy of this file of System Tracks; these copies are identical to the extent possible. For several alternative system configurations the study emphasized the data processing functions that need to be performed at the radar and Operations Facility sites to provide System Tracks.

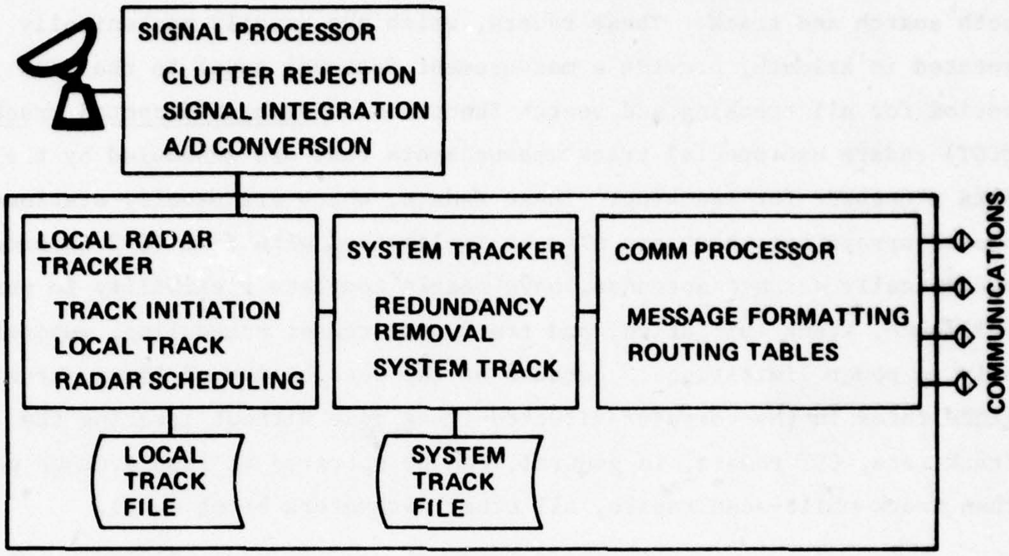
The functions to be performed at a typical radar site for one basic system configuration are indicated in Fig. 1.2(a). This study considered the functions performed in the large box. The study assumed that clutter-free (but not noise-free) digitized radar measurements are available from the radar signal processor. (The signal processing required to obtain these measurements was not included in the study.) These measurements are used by the radar in this configuration (in a manner determined by the study) to accomplish track initiation and maintain Local Tracks on the aircraft, which are kept in computer memory in the Local Track File. The Local Tracks are used by the System Tracker (again in a manner determined by the study) to help the netted system maintain the System Tracks, which are kept in the System Track File. In this basic system configuration, all nodes maintain a complete copy of the System Track File. These track functions require communications with the other nodes; the data processing required for communications was also a part of the study. The communications links themselves were not investigated.

The data processing functions performed at a typical Operations Facility are indicated in Fig. 1.2(b). The principal functions investigated in this study are the maintenance of the System Track File and the communications processing. The important function of providing usable displays of the vast amount of data in the System Track File was not addressed during the study.

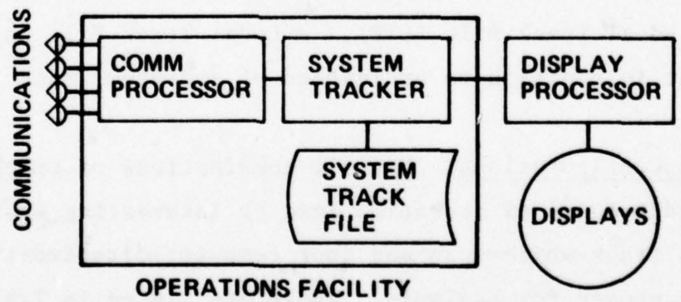
The specific technical accomplishments and results for each of the study tasks are summarized in following subsections.

1.3.2.1 Alternative System Configurations

During the study nine different system configurations were defined and analyzed for two basic radar modes (track-while-scan and computer-directed track) and for different track file structures. Three versions were simulated in the TACRAN (Tactical Air Control Radar Net) distributed system simulation to better understand their performance and demonstrate their viability. Data Processing and communications loads were defined for each configuration.



(a) Radar Site



(b) Operations Facility

Figure 1.2. Functional Areas Considered During Study

Radar Modes. Surveillance and tracking radars can operate in two basic modes. Track-while-scan (TWS) radars use search measurements for both search and track. These radars, which are usually mechanically rotated in azimuth, provide a measurement interval equal to the scan period for all tracking and search functions. Computer-directed track (CDT) radars use special track measurements that are scheduled by the data processor for tracking. These radars, which are usually stationary phased arrays but which can also be implemented with fast (1-3 seconds), mechanically scanned antennas, have nearly complete flexibility in surveillance, track initiation, and track measurement scheduling, subject only to power limitations. Because of the possibility of lower surveillance rates in the computer-directed-track mode without lowering the track rate, CDT radars, in general, can be operated at less average power than track-while-scan radars, all other parameters being equal.

Track File Structure and Location. The basic output of the system, the System Track File (STF), can be maintained at the Operations Facilities using various track-file structures at the radar sites. A System Track File might be maintained at every radar site, at selected sites, or only at Operations Facilities. Radars may independently maintain tracks using only their own measurements; these Local Tracks are maintained in a Local Track File (LTF). A Local Track File may be maintained at each radar in addition to or instead of a System Track File.

System Configurations. Not all combinations of track-file structures and radar modes of operation lead to interesting system configurations. Five track-while-scan and four computer-directed-track configurations were chosen for analysis. These are listed in Table 1.1. All Operations Facilities have a System Track File. As shown in the table, in some configurations fewer radars (the selected trackers) than can see an aircraft perform the tracking on that aircraft. In the other configurations, all of the radars track, with no tracker selection. This has a profound effect on the communications requirements of the various configurations.

TABLE 1.1
SYSTEM CONFIGURATIONS CONSIDERED

Configuration Number	Radar Mode*	Track Files at Radar†	Selected Trackers?
1	TWS	LTF and STF	No
2	TWS	Distributed LTF and STF	Yes §
3	TWS	LTF	No
4	TWS	STF	No
5	TWS	None	No
6	CDT	LTF and STF	Yes §
7	CDT	LTF and Partial STF	Yes
8	CDT	LTF	Yes
9	CDT	STF	Yes

*TWS--Track-While-Scan; CDT--Computer-Directed-Track.
†LTF--Local Track File; STF--System Track File.
§Favored configuration.

The design goal of the favored track-while-scan system concept, Configuration 2, was to overcome the inherent limitations of TWS radars, which typically scan at rates too low for reliable association of measurements with the tracks of highly maneuverable aircraft. In this system concept, tracking of each aircraft is performed cooperatively by a few selected radars to minimize communication requirements. The measurements from the selected radars are pooled to provide a single track on each aircraft at an effective measurement rate that is higher than the scan rate of the individual radars. Each tracking radar has a copy of this track, which is maintained in its Distributed Local Track File. A major criterion

in selecting the radars for tracking is that their observations of the aircraft be as evenly spaced as possible. The determination and control of which radars track which aircraft is totally distributed among the nodes with no centralized controller whatsoever, an attribute which increases the system survivability. The algorithms required to implement this configuration were developed in detail, and Configuration 2 was modeled in the TACRAN simulation.

In computer-directed-track operation the radars have sufficient freedom to perform track initiation and tracking at a high enough rate that each radar can individually track targets without having to pool measurements made by several radars as in the track-while-scan system just described. In the favored computer-directed track system concept, Configuration 6, all radars have both a Local Track File (LTF) and a System Track File (STF). Primary tracking of each aircraft is the responsibility of one selected radar, again to minimize communications requirements, with one or more backup radars tracking for survivability reasons.

Communications Requirements. The data rates required by the links in the network were determined for each of the nine configurations as functions of a number of such system parameters as number of radar sites, number of aircraft, system track update rates, etc. As an example, the data rates per link were calculated for each configuration for a specific set of parameter values; these are shown in Fig. 1.3. For a network of 70 radars tracking 1,000 aircraft, the data rates for the two favored configurations described above are about 40 kilobits per second per link, which is a reasonable data rate for point-to-point radio communications. Some of the other configurations require several hundred kilobits per second per link, and therefore are less favored configurations in terms of communications requirements.

Data Processing Requirements. The data processing rate requirements for each of the nine configurations were also expressed in terms of a

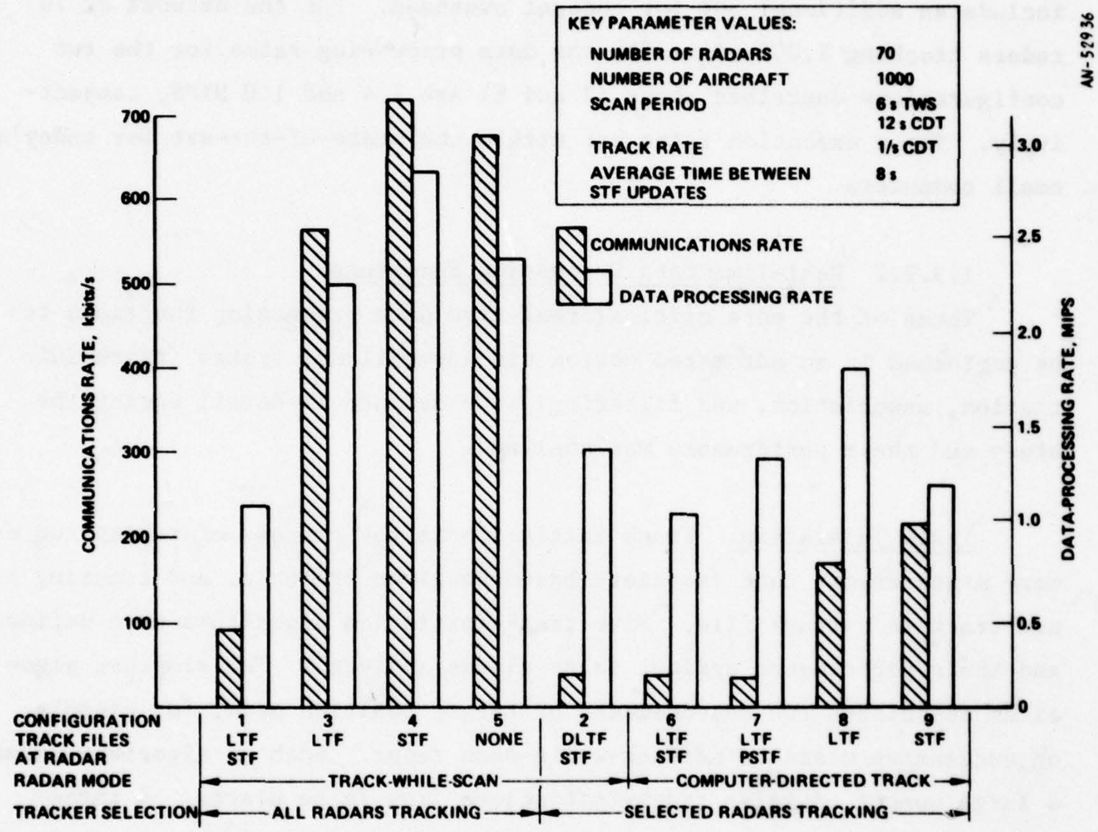


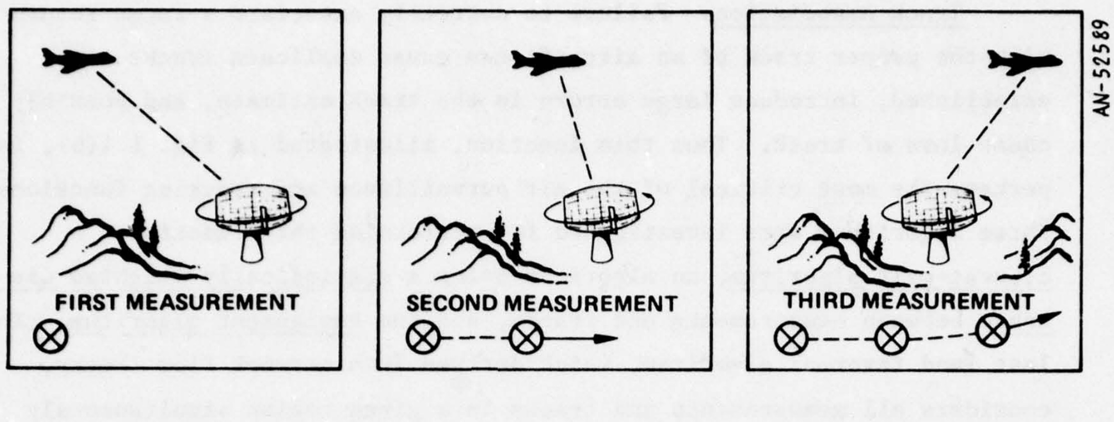
Figure 1.3. Comparison of Communications and Data Processing Rates

number of system parameters. The data processing rate in million instructions per second (MIPS) were calculated for each configuration for the same set of parameter values used in the communications requirements analysis; these example rates are also shown in Fig. 1.3. These rates include an additional 50% for control overhead. For the network of 70 radars tracking 1,000 aircraft, the data processing rates for the two configurations described above (2 and 6) are 1.4 and 1.0 MIPS, respectively. These execution rates are within the state-of-the-art for today's small computers.

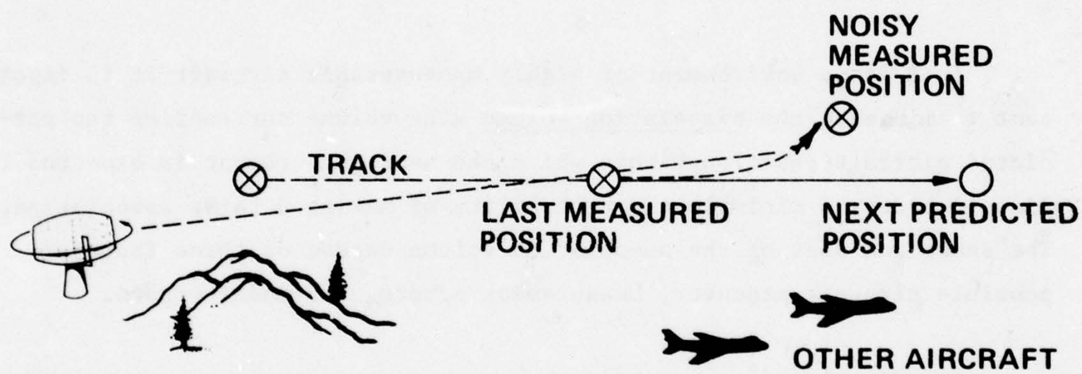
1.3.2.2 Real-Time Data Processing Functions

Three of the more critical real-time data processing functions to be performed in an automated netted air surveillance system (track initiation, association, and filtering) were defined in detail during the study and their performance was analyzed.

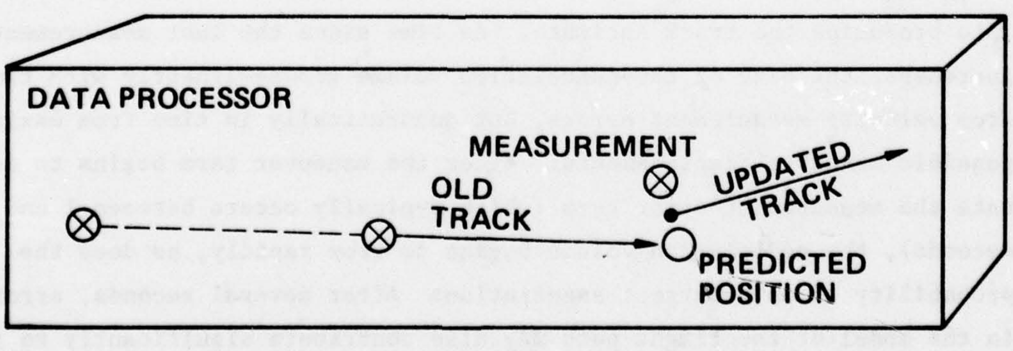
Track Initiation. Track initiation is the process of taking two or more measurements that associate based on given criteria, and creating a new track in a track file. Five track-initiation algorithms were defined and their performance against false alarms analyzed. The simplest algorithm associates two measurements of target position made, for example, on successive scans of a track-while-scan radar. Such an algorithm causes a large number of false track-initiations from false alarms. A three-measurement algorithm [illustrated in Fig. 1.4(a)] provides acceptable performance against false alarms if the scan rate is reasonably high. An algorithm that associates two pairs of measurements (from which two velocities can be derived) provides the best initiation performance in the presence of false alarms, but also requires that four successive measurements be detected, a burden if the individual probability of detection is not high. A fourth algorithm requires that one measurement pair (from which velocity is derived) be associated with one of the second measurement pair, improving the overall probability of detection. The fifth track-initiation algorithm associates two pulse-Doppler measurements. The last two also provide acceptable performance.



(a) Track Initiation



(b) Track Association



(c) Track Filtering

Figure 1.4. Critical Real-Time Data Processing Functions

Track Association. Failure to correctly associate a radar return with the proper track of an aircraft can cause duplicate tracks to be established, introduce large errors in the track estimate, and possibly cause loss of track. Thus this function, illustrated in Fig. 1.4(b), is perhaps the most critical of the air surveillance and tracking functions. Three algorithms were investigated for performing this function: a closest-pair algorithm, an algorithm using a statistically weighted distance between measurements and tracks, and the assignment algorithm. The last (and favored) algorithm, which derives from network flow theory, considers all measurements and tracks in a given region simultaneously and pairs them by minimizing the sum of the squares of the distances between measurements and tracks.

In a dense environment of highly maneuverable aircraft it is important to minimize the association volume--the volume surrounding the predicted aircraft position within which the next measurement is expected to lie--in order to minimize the probability of making a false association. The shape and size of the association volume depend on three factors: possible aircraft maneuver, measurement errors, and model errors.

Immediately after updating the track from a new measurement, the primary contributor to the size of the association volume is measurement noise--the errors in the latest and the previous measurements that went into producing the track estimate. As time since the last measurement increases, the size of the association volume grows--linearly with time from velocity measurement errors, but quadratically in time from maximum possible maneuver displacements. After the maneuver term begins to dominate the measurement-error term (which typically occurs between 1 and 3 seconds), the association volume begins to grow rapidly, as does the probability of an incorrect association. After several seconds, errors in the model of the flight path may also contribute significantly to the size of the association volume. Therefore it is important to keep the measurement interval between 1 and 3 seconds if possible.

The shape of the association volume as it grows with time since the last measurement is shown in Fig. 1.5 for a track whose last estimated velocity is 300 m/s (670 mph). Only the growth of the association volume due to possible aircraft maneuver is shown (in two dimensions) in the figure. Assuming the aircraft can maneuver up to 10g laterally and up to ±2g axially, the possible positions of the aircraft 2, 5, and 10 seconds after the last measurement are outlined. As an example, an 8g turn is shown. After only 10 seconds the aircraft is more than 3 km from the predicted position, which makes a correct association highly unlikely in a dense aircraft environment. A higher data rate is clearly indicated. Note also that the association volume is concave, a difficult shape to represent in a computer, although reasonable approximations may be practical.

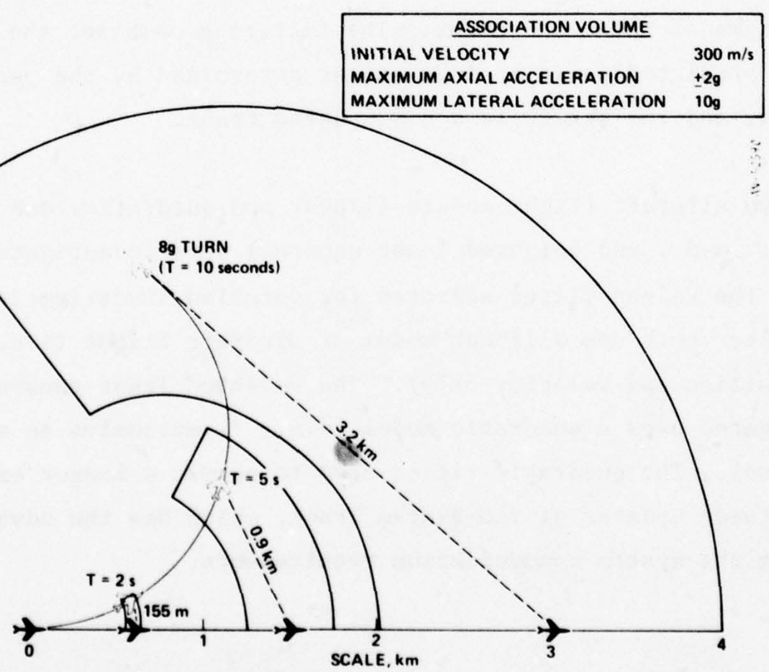


Figure 1.5. Association Volume

The most difficult association problem occurs when the local aircraft density is very high--where several aircraft aircraft are close together either because they are flying in formation or because they happen to be on flight paths that bring them close together for a short time. The study considered a number of typical situations, and also analyzed the performance of the assignment algorithm in one simple situation.

Track Filtering. The principal objective of the surveillance systems studied is to keep track of aircraft; very accurate track is not a requirement at this time nor is such a requirement foreseen in the future. This is primarily because all weapons delivery systems have their own end-game sensors. Thus the data rate and measurement accuracy requirements for track filtering are not as exacting as those for association.

The track filtering process is illustrated in Fig. 1.4(c). When a measurement is associated with the track, the track is predicted ahead to the time of the measurement. The filtering combines the measurement and the predicted position in a manner determined by the particular filter used, and the result is a new updated track.

Two aircraft flight models (linear and quadratic) and three filters (Kalman, α-β , and weighted least squares) were investigated during the study. The Kalman filter selected for detailed investigation and the α-β filter both use a linear model of aircraft flight (i.e., they estimate position and velocity only). The weighted least-squares filter investigated uses a quadratic model (i.e., it estimates an acceleration term also). The quadratic fit is used to permit a longer extrapolation time between updates of the System Track, which has the advantage of reducing the system communication requirements.

Based on the results of the study of tracking filters, it is believed (but not proven due to lack of time) that the filter to use in a tactical air surveillance and control system is one which uses a quadratic aircraft flight model (to minimize updates of the System Tracks), and the simplest recursive algorithm that can be implemented. A candidate is the $\alpha-\beta-\gamma$ filter, which was not investigated in detail during the study.

1.3.2.3 Radar Data Requirements

The primary requirement on the radar as determined during the study is on the measurement rate, which must be sufficiently high to provide an acceptably low rate of false track initiation and reliable association of measurements with tracks. The latter need dominates. A measurement rate of from 1-3 seconds should be achieved--either by a single computer-directed track radar or by pooling measurements from several track-while-scan radars--to achieve a high probability of correct association.

For a system whose primary purpose is to keep track of targets, rather than to know their positions very accurately, there is little purpose in making very accurate measurements. Unless the data rate is extremely high, track accuracy is dominated by maneuver errors. For tracking there appears to be no purpose in having range accuracy better than angle accuracy. For association of measurements with track, however, good range resolution is required to separate targets. Range resolution between 20-50 meters and angle resolution between 1-2 degrees should be adequate. Range-rate measurements aid the association process, but not tracking.

1.3.3 In Summary...

Given a future requirement for a highly survivable tactical air surveillance and control system that can provide continuous, non-redundant tracks on large numbers of aircraft, some of which may be highly maneuverable and at very low altitudes, a system like those investigated is necessary. This study has made some basic progress towards understanding

automated netted tactical air surveillance systems and has shown that such a system is feasible with reasonable radar, communication, and data processing requirements.

2 SUMMARY OF VOLUME 2, "TECHNICAL DETAILS"

Volume 2 of this report, "Technical Details," gives a detailed presentation of the technical analyses and results of the study. It is divided into three sections: The first section discusses the basic system concept, and describes and analyzes alternative configurations. The second section discusses and analyzes the real-time data processing functions required by such a system. The TACRAN simulations which were used during the study are described in detail in the third section.

2.1 SYSTEM CONCEPT, ALTERNATIVES AND ANALYSES[1]

Section 1 of Volume 2 contains descriptions and analyses of the alternative system configurations considered during the study. These include discussions of the basic system concept, radar characteristics and requirements, system configurations, communications, and data processing. This section summarizes each of these topics.

2.1.1 Basic System Concept

The basic concept for the tactical air surveillance and control system investigated during the study is depicted in Fig. 1.1 on page 13 of this volume. This concept, summarized in Sec. 1.1, beginning on page 11 of this volume, is an automated, non-hierarchically netted system conceived to track large numbers of aircraft, many of which are highly maneuverable and capable of flying at low altitudes.

2.1.2 Radar Characteristics and Requirements

The two basic radar operational modes defined in Sec. 1.3.2.1 on page 16, track-while-scan (TWS) and computer-directed-track (CDT), can be achieved by several antenna configurations listed in Table 2.1. Generally, mechanically scanned antennas are used in TWS radars and phased arrays are used in CDT systems, but other types of antenna configurations are possible. The mechanically scanned antennas can be either reflectors or

[1]Except for the initial section number (2.) the numbering in this section follows that of Volume 2.

TABLE 2.1

RADAR ANTENNA CONFIGURATIONS AND OPERATIONAL CONCEPTS

Antenna Configuration	Operational Mode	Surveillance	Track Initiation	Tracking
1. Mechanically Scanned in Azimuth at Low Rate (4-12 s)	Track-While-Scan (TWS)	At scan rate		
A. Reflector			Successive scans	Fixed spacing at scan rate
B. Phased Array			Pairs on same scan	Adjustable timing within window
2. Mechanically Scanned in Azimuth at High Rate (1-3 s)	Computer-Directed Track (CDT)	Slower than scan rate		
A. Reflector			Successive scans	Fixed spacing at scan rate
B. Phased Array			Pairs if needed	Somewhat higher rate possible with non-uniform spacing
3. Stationary Phased Array	Computer-Directed-Track (CDT)	Adaptable		
A. Single Face			Measurement pairs or trains	Adaptable; independent of scan rate
B. 360-Degree Coverage			Measurement pairs or trains	Adaptable; independent of scan rate

planar phased arrays. If the scan rate is relatively low, the radar must operate in a TWS mode. At a high scan rate, surveillance can be performed at a low rate to conserve power while tracking is performed at the scan rate, providing essentially a computer-directed-track capability. A stationary phased array provides complete flexibility in surveillance, track-initiation, and track scheduling. Multi-face or specially designed arrays can provide 360-degree coverage in azimuth, but a network of single-face planar arrays might also be used to provide complete coverage of a specified volume; the coverage of such radars is discussed below. The implementation of the surveillance, track initiation, and tracking functions depends on the radar mode of operation and antenna configuration as indicated in Table 2.1.

For each of the antenna configurations, the radars can be designed to measure only the range and azimuth coordinates of the target position;

such two-dimensional (2-D) radars were given little consideration in the study in accordance with the Statement of Work. With appropriately designed antennas, the radars can also measure the target elevation or height, the third dimension, and are accordingly sometimes called 3-D radars. With appropriate waveforms and signal processing, it is possible for the radars to measure Doppler velocity, but these fourth-dimension measurements can be highly ambiguous and provide little useful additional tracking information; only limited consideration was given to the use of Doppler-velocity measurements.

Relative Power Requirements. The relative power requirements of track-while-scan (TWS) and computer-directed-track (CDT) radars were compared to determine the relative energy required for the additional transmissions used for track initiation and tracking. The results show that even with large numbers of targets in track, track initiation and tracking only require a few percent additional energy over that required for search. Since the search rate can be reduced considerably in a CDT system over a TWS system--perhaps by as much as 50%--the total energy requirement of a CDT system can be much less than that of a TWS system.

Planar-Array Coverage Capabilities. The stationary, single-face phased array is less costly than arrays with full hemispherical coverage and may provide greater mobility. Since, with a stationary, single-face array, the radar power available for surveillance is concentrated in a sector limited by the maximum scan angle, the surveillance range is greater than for 360-degree coverage, assuming the same average power. This increase in range partially compensates for the reduction in angular coverage, so that the surveillance volume coverage of a single-face array with a maximum scan angle of ± 60 degrees is 53% of that of a radar with 360-degree antenna coverage if the scan times are equal. If the 360-degree-coverage radar operates in a TWS mode, then the single-face radar operating in the CDT mode can usually scan at a lower average rate. The relative

surveillance coverage increases to 75% for a scan rate half that of the 360-degree-coverage radar and to 92% for a relative scan rate of one third. Thus if the longer average scan times are reasonable, as they appear to be, the surveillance area coverage with a stationary, single-face phased array can be nearly as great as with a mechanically scanned antenna.

2.1.3 System Configurations

To provide a basis for analyzing and comparing the requirements and feasibility of a variety of alternative implementations of the basic system concept, a number of representative system configurations were defined. The basic differences between these configurations are (1) their track file structure and location, and (2) their radar mode of operation--track-while-scan (TWS) or computer-directed-track (CDT). The combinations of the System Track File (STF) and Local Track Files (LTF) at the radar sites considered during the study are shown in Fig. 2.1, which also shows that each Operations Facility has a copy of the System Track File.

The system operation and data requirements also depend on the radar mode of operation. The major functional difference between the track-while-scan (TWS) and the computer-directed-track (CDT) modes is that a CDT capability enables each individual radar to track independently at a rate high enough for reliable association under most conditions. This capability can be exploited by selecting a few radars (from the 25 or so within range) to track each target. With TWS radars, a high tracking rate can be obtained only if selected radars track each target cooperatively by combining their measurements.

All combinations of the track file organizations of Fig. 2.1, radar modes of operation, and the use of selected or all possible radars for tracking lead to many conceivable system configurations of which some are clearly more reasonable or interesting than others. The nine system configurations listed in Table 1.1 on page 19 were selected as representative combinations for further analysis.

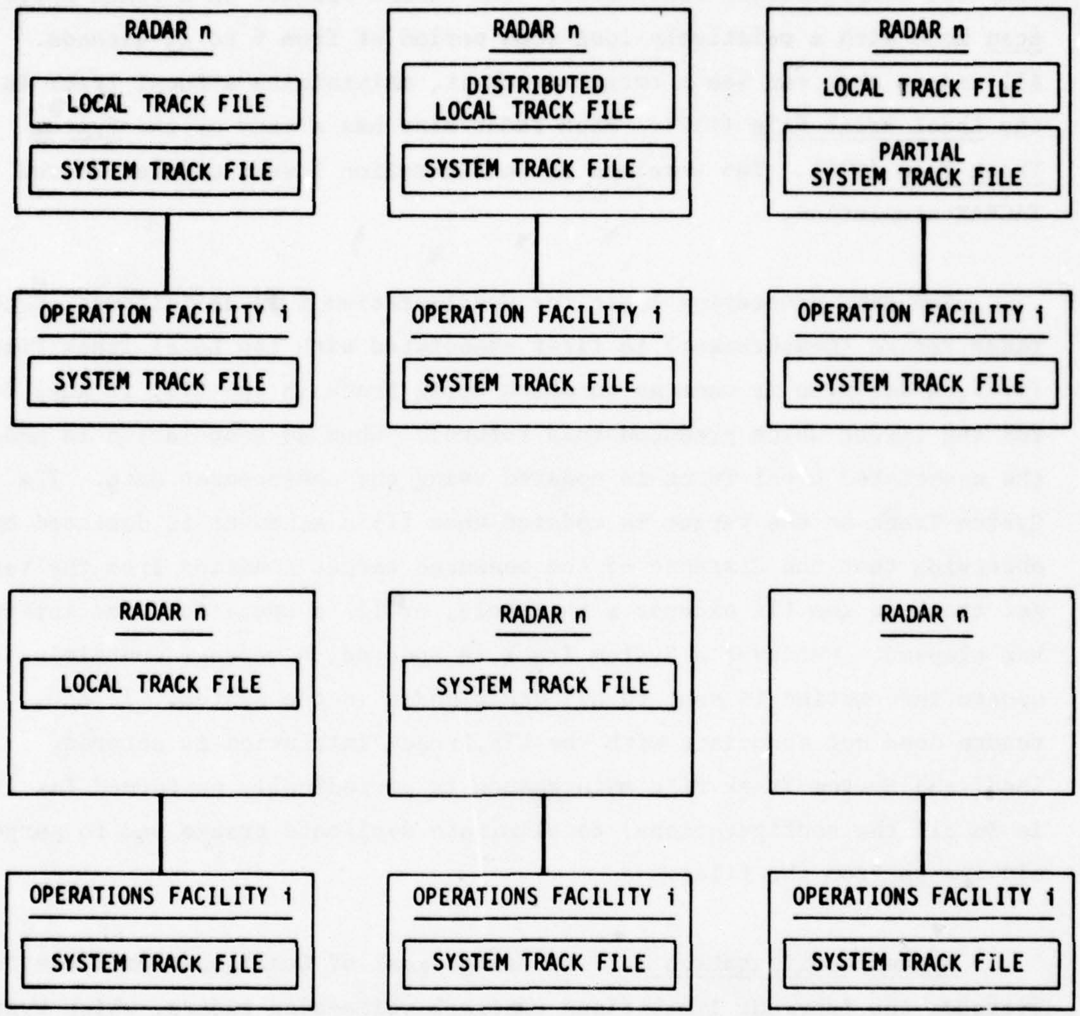


Figure 2.1. Six Variations of Track File Structure at the Radar Sites

The operation of each of the system configurations is described in Volume 2 with the aid of a flow chart or top-level logic diagram. These descriptions are summarized below. More detailed summaries are given for two of the more interesting configurations (2 and 6).

System Configuration 1. Configuration 1 is the most basic and simplest configuration considered. The radars operate in a track-while-scan mode with a relatively long scan period of from 4 to 12 seconds. All radars that can see a target track it, maintaining a Local Track in the Local Track File (LTF). Each radar also has a copy of the System Track File (STF). Two versions of Configuration 1 were modeled in the TACRAN simulation.

The data processing logic for Configuration 1 is as follows: Each radar return (measurement) is first associated with the Local Track File (i.e., a decision is made as to which Local Track in the LTF, if any, is for the target which produced this return). When an association is made, the associated Local Track is updated using the measurement data. The System Track on the target is updated when (1) a maneuver is detected by observing that the distance of the measured target position from the target track in the LTF exceeds a threshold, or (2) a specified time interval has elapsed. Whenever a System Track is updated, a message containing the update information is sent to all other nodes in the system. If the return does not associate with the LTF, track initiation is entered. Local and System Track File maintenance is periodically performed (as it is in all the configurations) to eliminate duplicate tracks and to purge old tracks from the files.

System Configuration 2. The design goal of Configuration 2 was to overcome the inherent limitations of track-while-scan radars, which typically scan at rates too low for reliable association of measurements with the tracks of highly maneuverable aircraft, while still using the track-while-scan mode. In this system concept, tracking of each aircraft is performed cooperatively by a few selected radars to minimize communication requirements. The measurements from the selected radars are pooled to provide a single track on each aircraft at an effective data rate that is higher than the scan rate of the individual radars. Each tracking radar has a copy of this track which, since it is distributed among several

radars, is called the Distributed Local Track, is maintained in its Distributed Local Track File (DLTF). The determination and control of which radars track which aircraft is totally distributed among the nodes with no centralized control whatever, an attribute which increases system survivability. Each radar also has a copy of the System Track File (STF). The algorithms required to implement this configuration were developed in detail, and Configuration 2 was modeled in the TACRAN3 simulation.

A flow chart for this system concept is shown in Fig. 2.2. If a new radar return (measurement) associates with the Distributed Local Track File (DLTF), the return is processed through the Tracker Selection and Track Update Logics (described below). If it does not associate with the DLTF, then this radar is not presently a tracker of this target. In this case the return is checked to determine if it associates with the Non-Track File (the NTF is the portion of the System Track File which contains all of the System Tracks except for those on targets being tracked by the local radar), then the Tracker Selection Logic is also entered. Because the System Tracks are not maintained as accurately as the Distributed Local Tracks, in the process of determining whether or not a return associates unambiguously with a track in the NTF (STF), it may be necessary to obtain the distance between the measurement and the extrapolated track from a more up-to-date, and presumably more accurate, estimate of the track as provided by the DLTF at another radar which is maintaining the track. If the return does not associate with the DLTF or the NTF (STF), the three-measurement track initiation procedure is entered.

The Tracker Selection Logic involves computations and decisions to determine if this radar should continue to be or should become a tracker of this target. It is entered every time a radar associates a measurement with a track. A major criterion for tracker selection is that the measurement times of the set of trackers be as evenly spaced as possible. Other criteria consider the present number of trackers and the range and range rate of the target.

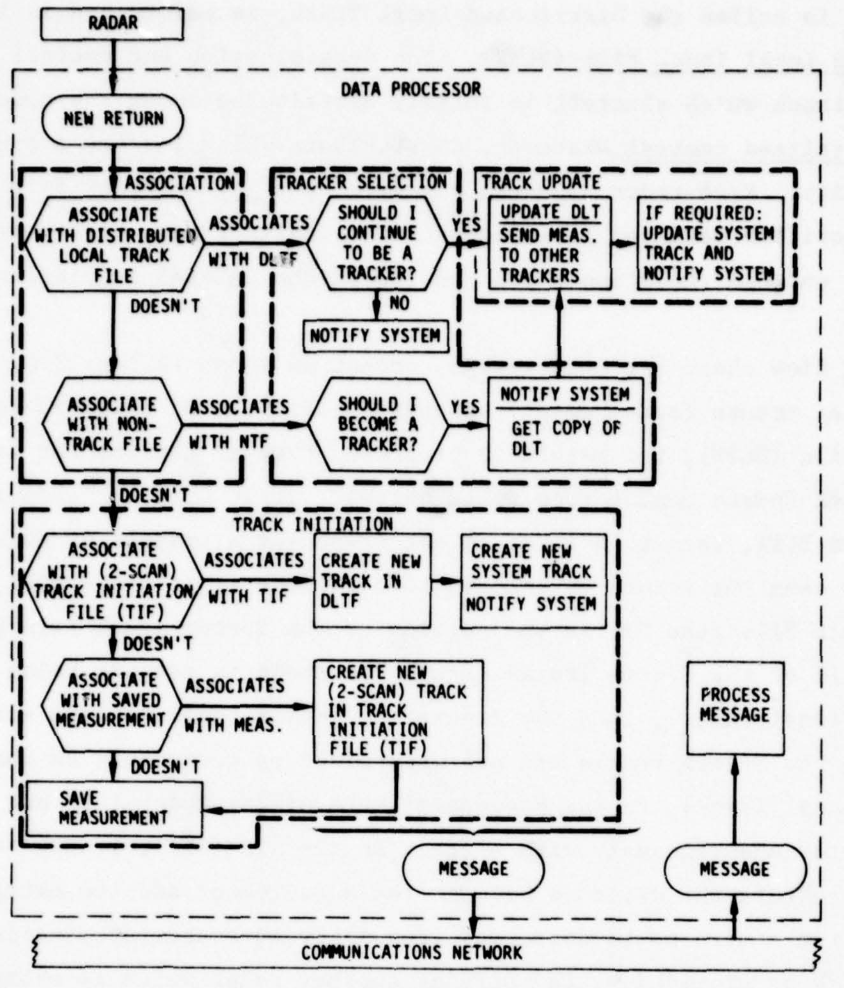


Figure 2.2. Flow Chart for TWS Operation With DLTF and STF at Each Radar and Selected Radars Tracking (Configuration 2)

<u>System Configuration 3</u>. This system configuration is similar to the first system described above except that there is <u>no System Track File</u> at the radars, only a <u>Local Track File</u>. All of the <u>track-while-scan</u> radars track all targets that are within range. Since the STF exists only at the Operations Facilities, all STF update messages are sent only to these nodes. The data processing logic is similar to Configuration 1 except

for the track labeling and association of the Local Track with the System Track, which must be done at the Operations Facilities.

System Configuration 4. In this track-while-scan configuration, each radar has a copy of the System Track File, but no Local Track File. With no LTF at the radars, the returns must be associated with the STF. Each time a radar updates its copy of the STF, it must send the update to all other nodes (since by definition the STF is the system file that is identically maintained at every node). It is also assumed in this configuration that all radars that can see a target track it.

System Configuration 5. This track-while-scan configuration has no track files at the radars. The only track files in the system are copies of the System Track File at each of the Operations Facilities. With no track files at the radars, the parameters describing each detection (i.e., the measurement itself) must be sent to the Operations Facilities for further processing. There the measurements are associated with the STF, and for targets that are in track, the STF is updated with each measurement.

System Configuration 6. Configuration 6 is the first of the systems in which the radar operate in the computer-directed-track mode. A major difference between TWS and CDT operation is that CDT transmissions are scheduled for specific purposes such as surveillance, track initiation, and tracking, and the returns are processed according to the function being performed. In Configuration 6, which includes both a Local Track File and a System Track File at each radar, this operational concept is reflected in the flow chart of Fig. 2.3, which is one possible implementation of a CDT system. At the left side of the flow chart, the three types of returns of primary interest are routed to different portions of the logic diagram by the Returns Distribution logic. At the right side, after the return-signal data have been appropriately processed, requests for subsequent transmissions are sent to the Radar Scheduler.

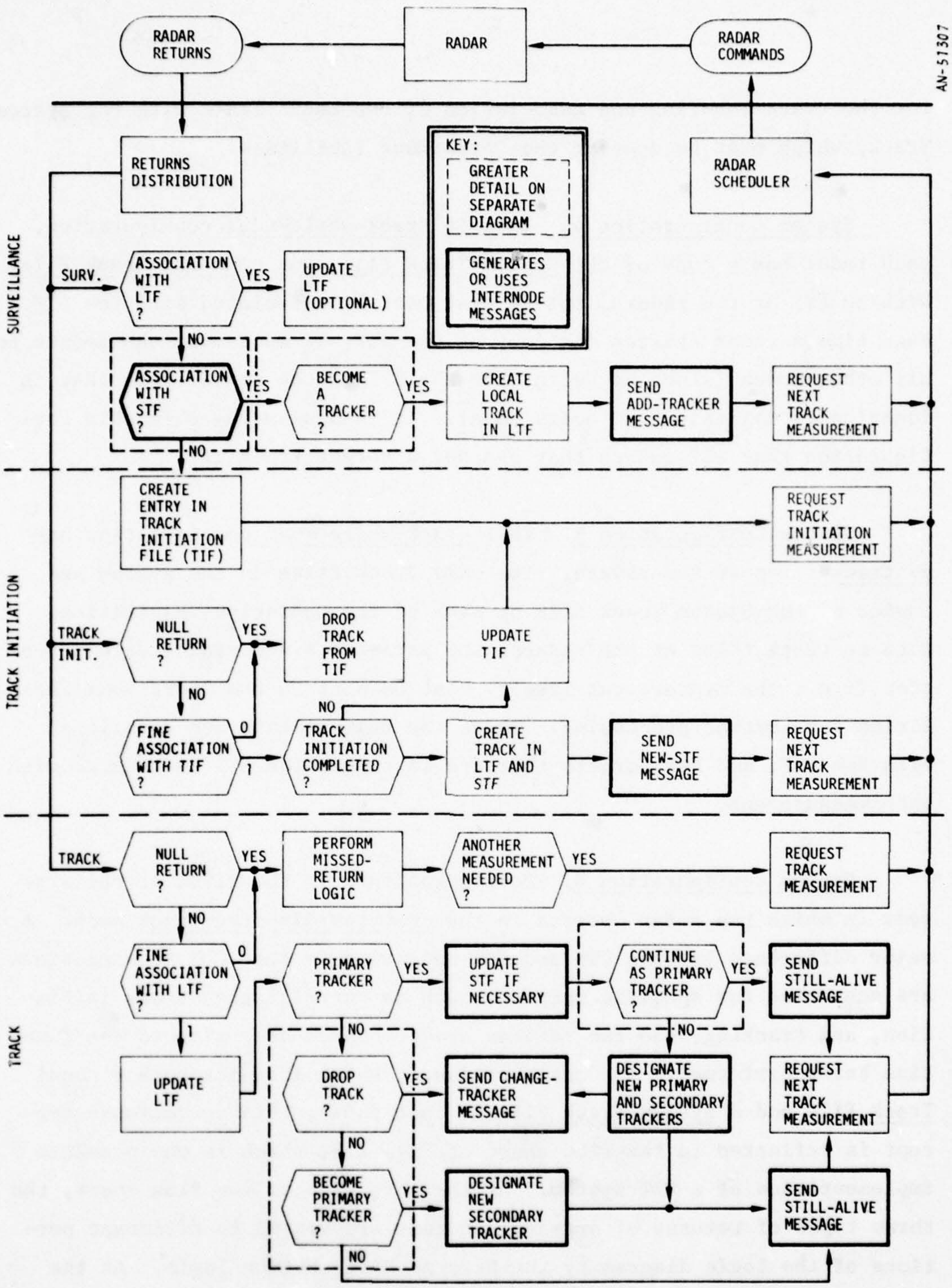


Figure 2.3. Flow Chart for CDT Operation With an LTF and STF at Each Radar and Selected Radars Tracking (Configuration 6)

Thus the operation of the radar and data processor constitutes a closed-loop process.

Surveillance returns are associated first with the Local Track File to see if the target is being tracked by this radar. If not, these returns are then associated with the System Track File to see if the target is being tracked by any radar. If it is being tracked by other radars, logic to determine whether or not this radar should become a tracker is entered. If the target is not in track by any radar the track-initiation process is entered.

The returns from track transmissions are already tagged with the label of the track. However, a fine association is performed with particular entries in the Local Track File to make sure that the return is from the intended target. If the outcome is positive as expected, the Local Track is updated. If this radar is the primary tracker for this target, the System Track is updated if the deviation of the Local Track from the System Track exceeds a specified threshold. Logical operations are then performed to determine whether this radar should drop track, become a primary tracker, or continue as the primary tracker.

System Configuration 7. The next computer-directed-track system configuration is a modified version of Configuration 6. Each radar has a Local Track File, but instead of maintaining the complete STF at every radar, only a Partial System Track File (PSTF) is maintained at each radar. This PSTF contains the track data for only those targets in track which are within the coverage volume of the radar, i.e., can possibly be seen by the radar. The reason for considering the use of such a Partial System Track File is to reduce the communications requirements by limiting the dissemination of the STF updates to those radars which need these data for association with the surveillance returns. Once a target is in track and its position is known, the radars which are likely to be able to see the target can be determined by the primary tracker, and the STF updates

can then be transmitted by the primary tracker to only those radars. Of course, a complete STF must be maintained at the Operations Facilities for use in the planning and control operations.

System Configuration 8. In this computer-directed-track configuration, each radar has only a Local Track File. With no System Track File at the radars, all of the surveillance returns which do not associate with the LTF must be sent to an Operations Facility for association with the STF. With this modification--the elimination of the check for association with the STF at the radars--the logic for this system configuration is the same as that for Configuration 6. As in the other CDT systems, several radars are selected to track each target and one of these is designated the primary tracker and another the secondary tracker. The LTF is updated with each tracking measurement, and the STF is updated when a maneuver is detected by the primary tracker based on the deviation of a measurement from the predicted target track (or when a specified time has elapsed). The STF updates are, of course, sent only to the Operations Facilities, not to any of the radars.

System Configuration 9. The last computer-directed-track configuration has only the System Track File at each radar. With no Local Track Files at the radars, both the surveillance and tracking returns must be associated with the System Track File at each radar. The STF must be updated with each tracking measurement made by the primary tracker since no other track file is maintained. As with the other CDT systems considered, each target is tracked by a few selected radars, including one designated the primary tracker and another the secondary tracker.

2.1.4 Communications

The communications data-rate requirements of the nine system configurations described in the preceding section were analyzed by identifying the types of messages sent, estimating their length, and determining the rate at which they are sent. This analysis and its results include

both parametric expressions for the communications data rates and numerical examples based on a particular set of parameter values.

It is important to note that the communication data rates were calculated primarily for comparative purposes and to gain insight into the effects of various parameters on communication requirements. They are not to be considered as definitive statements of bandwidth requirements. In particular, the data rates presented are averages over the temporal variations and the spatial distributions of the targets although the worst-case netting geometry is considered.

There are two types of messages used in the nine alternative system configurations: system messages and directed messages. A system message is one which is sent to all other nodes in the system. It contains information required by all other nodes, such as a message to update a particular System Track. A directed message is one which is specifically addressed to one or a few nodes. With the algorithm used for transmitting system messages to every node in the system, each message traverses every communication link once (in one of the two directions).

Each message consists of a header, text, and a cyclic redundancy check (CRC). The header and CRC require 44 bits for a system message and $44 + 8N_R$ bits for a directed message, where N_R is the number of receiver nodes for the message. The number of bits in the text depends on the message content; the text length was determined for each type of message in each of the nine alternative system configurations.

System Parameters and Example Values. In addition to the message length, the required bandwidth of the communications links depends on the values of a number of system parameters. In Volume 2, the communication data rates for the system configurations under consideration are expressed in terms of these parameters. These expressions are also evaluated as examples for a particular set of parameter values.

The values used in the examples are derived from an example deployment of 70 netted radars covering approximately a 270-km square ($\sim$20,000 n mi^2). The radars are spaced 30 km apart and have a range of from 80-90 km. With such a deployment, up to 25 radars can see each aircraft (that is not so low that it is masked by terrain). A total of 1,000 aircraft are assumed to be in the surveillance volume for the example calculations. Nearly all of the data-rate components scale linearly with the number of aircraft. These and other parameters needed in the communication data rate calculations are listed in Table 2.2, along with the values of the parameters used in the data-rate examples. (The rationales for these example values are given in Volume 2.)

Data Rates. The data rates presented are those over the most heavily used link in the system. This worst-case link is one involved in communicating with an isolated node--one which is connected to the rest of the network by only one (two-way) link because of equipment failures or because enemy actions which have rendered the other links inoperative. This situation is a worst case in that all messages to or from the node must traverse a single link, leading to the maximum required data rate over the link. The incoming and outgoing data rates are calculated and presented separately. In system configurations in which the System Track File is maintained at only a few nodes, it is similarly assumed that the STF nodes are connected to the rest of the network by only a single link, and the data rates are calculated for the messages into and out of the STF node. While the incoming single-link data rates that are presented here are peak values in the network-geometry sense described above, they are averages in terms of the spatial distribution of the targets in the surveillance volume and the temporal variations of the communications traffic.

In this summary, only one example of the data rate calculations is presented; the full results are given in Volume 2. In Configuration 2, with only selected radars tracking each target and a Distributed Local

TABLE 2.2

PARAMETERS INVOLVED IN THE COMMUNICATIONS ANALYSIS

Symbol	Parameter	Value for Example
F	Fraction of Returns for Which a Distance Must be Obtained	0.5
N	Number of Nodes (Radars)	70
N_A	Number of Targets (Aircraft)	1,000
N_F	Number of False Alarms Per Scan Per Radar	100
N_O	Number of STF Nodes (Operations Facilities)	3
N_S	Number of Radars Within Tracking Range of a Target	25
N_T	Number of Radars Tracking a Target	3
T_A	Time Between Still-Alive Messages From Each Radar	1 s
T_C	Average Time Between Change of Tracking Radars for Each Target	50 s
T_H	Average Time Between Help Messages for Each Target	100 s
T_L	Average Time Between STF Label Messages for Each Target	20 s
T_P	Average Time Between Change of Primary (and Secondary) Trackers for Each Target	50 s
T_R	Average Time Between S/N Updates for Each Target	3 s
T_S	Average Radar Search Period	6 s for TWS 12 s for CDT
T_T	Time Between Tracking Measurements on Each Target (CDT Configurations)	1 s
T_U	Average Time Between STF Updates for Each Track	8 s

Track File (DLTF) and STF at each of these radars, a number of types of messages must be transmitted from node to node. These message types are listed in Table 2.3; their purpose and content are described in detail in Sec. 3.5 of Volume 2.

As an example of the steps involved in determining the data rates consider the STF update message, the largest contributor to the total incoming message data rate. The total length of the message, including the header (which includes the bits for the trailing cyclic redundancy check) and text, is 250 bits. For each target this message is sent an average of every T_U seconds (for a rate of $1/T_U$ per second).

The number of targets for which a STF Update message is received by each node is the total number of targets in track (N_A) minus the portion

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TABLE 2.3

COMMUNICATIONS DATA-RATE REQUIREMENTS FOR CONFIGURATION 2

(TWS Operation--DLTF and STF at Each Radar--Selected Radars Tracking)

Incoming Messages

Message	Message Length, bits			Messages/s per Target	Number of Targets	Data Rate per Link, kbits/s	
	Header	Text	Total			Equation	Example
Distance Request	10*	85	95	$F(N_S-N_T)/T_S$	N_A/N	$0.095FN_A(N_S-N_T)/NT_S$	2.5
Distance Reply	10*	32	42	F/T_S	$N_A(N_S-N_T)/N$	$0.042FN_A(N_S-N_T)/NT_S$	1.1
DLT Request	52	24	76	$1/T_C$	N_A/N	$0.076N_A/NT_C$	0
DLT Reply	52	439	491	$1/T_C$	N_A/N	$0.491N_A/NT_C$	0.1
Measurement	52	77	129	$(N_T-1)/T_S$	N_AN_T/N	$0.129N_AN_T(N_T-1)/NT_S$	1.8
STF Update	44	206	250	$1/T_U$	N_A-N_A/N	$0.250N_A(N-1)/NT_U$	30.8
Drop Tracker	44	24	68	$1/T_C$	N_A-N_A/N	$0.068N_A(N-1)/NT_C$	1.3
Add Tracker	44	47	91	$1/T_C$	N_A-N_A/N	$0.091N_A(N-1)/NT_C$	1.8
Help	44	40	84	$1/T_H$	N_A-N_A/N	$0.084N_A(N-1)/NT_H$	0.8
						Total	40.2 kbits/s

of these targets for which the radar at that node is responsible (an average of N_A/N). The expression for the data rate in bits per second is simply the product of the message length in bits times the number of messages per second for each target times the number of targets. This product for the incoming STF Update messages (after dividing by 1,000 to convert to kilobits per second per link) is given in the next-to-last column in the form of an equation. This equation is evaluated for the example parameter values given in Table 2.2 in the last column.

The communications data rates calculated as examples using the parameter values in Table 2.2 for each of the nine system configurations considered are summarized in Table 2.4. The sum of the incoming and outgoing data rates over a single link to an isolated node is given along with the separate values of these two rates. The incoming data rates,

TABLE 2.4

SUMMARY OF COMMUNICATIONS DATA-RATE REQUIREMENTS

	Data Rate in kbits/s Over Link to Isolated Node		
Configuration Number	Incoming	Outgoing	Total
1	90	1	91
2	40	5	45
3	564*	12*	576*
4	719	10	729
5	678*	10*	688*
6	37	4	41
7	37	6	43*
8	168*	83*	251*
9	216	4	220

*Over link to Operations Facility or STF node only.

which are considerably larger than the outgoing rates in all cases, are plotted in Fig. 1.3 on page 21. As indicated in the table, the data rates for some configurations are for any node in the network which through attrition becomes connected by only one link to the rest of the network (and in fact the sum of the incoming and outgoing rates for this node is approximately equal to the total two-way data rate on any link in the network), while for other configurations the data rates are those on the high-traffic links leading to and from the Operations Facilities located at certain radar/data processor nodes. In these latter configurations, all the links would have to have sufficient capacity to accommodate the indicated data rates if the Operations Facility could be located at any node, but many of the links would not be operating at their full capacity at any given time and the excess bandwidth might be used for ECCM purposes.

For the example results summarized in Table 2.4, the communications data rates are lower for configurations in which there is both a Local Track File and System Track File of some sort at each node than for configurations in which there is only one or none of these types of files at each node. The data rates are generally lower for the computer-directed-track systems with selected radars tracking than for the track-while-scan systems with all radars within view tracking each target. However, the data rate for the only track-while-scan (TWS) system in which selected radars are used for tracking (Configuration 2) is comparable to the lowest data rate for the computer-directed-track (CDT) systems. These lower data rates (of the order of 40 kilobits per second) lead to communications bandwidth requirements which are certainly reasonable for line-of-sight communication links.

2.1.5 Data Processing

To obtain an indication of the data processing requirements for the highly redundant netted systems under consideration, a estimate was made of the data-processing execution rates in millions of instructions per

second (MIPS) for each of the nine alternative system configurations. The resulting MIPS counts are for "traditional" types of instructions, such as those performed by the Control Data 6000-series of machines.

The procedure followed in determining the data-processing rates consists of three basic steps: (1) the number of instructions required to perform each of the major data-processing operations was estimated, with the aid of the TACRAN3 simulation where possible; (2) for each system configuration of interest, the rates at which each operation is performed were specified as functions of the threat and system parameters; and (3) the number of instructions was multiplied by the repetition rate for each operation, the resulting expressions were evaluated for example values of the parameters, and the data-processing rates for all of the operations performed by a particular system were summed to obtain the data processing requirements for that configuration.

Configuration 2 will be used here to illustrate this procedure and the results it produces; similar analyses for all the configurations are given in Volume 2. The required data processing operations are in Table 2.5, along with the numbers of instructions that must be executed for single iterations of the operations. The repetitions per second are stated in terms of the same parameters listed in Table 2.2 used for the communications analysis, plus a few additional parameters listed in Table 2.6.

The data-processing execution rate in instructions per second for each operation is just the expression for the number of repetitions per second multiplied by the number of instructions per repetition. Values of the execution rates in thousands of instructions per second (TIPS) are given in the last column for each of the operations for the example parameter values specified in Tables 2.2 and 2.6. These values are summed to obtain the average data-processing execution rates. This sum is increased by 50% to account for control overhead to obtain the total

TABLE 2.5

DATA PROCESSING REQUIREMENTS FOR CONFIGURATION 2

(TWS Operation--DLTF and STF at Each Radar--Selected Radars Tracking

Operation	Number of Instructions	Repetitions per Second	Execution Rate, TIPS Example Values
Coordinate Transformation	100	$(N_A N_S/N+N_F)/T_S$	7.6
Track Initiation	6,900	S_R+N_F/T_S	121.9
Association With LTF	3,700	$(N_A N_S/N+N_F)/T_S$	281.9
Association With STF	4,500	$N_A(N_S-N_T)/NT_S+N_F/T_S$	310.7
Local Track File Update	900	$N_A N_T/NT_S$	6.4
Track File Maintenance			
Track Initiation File	2,000	$1/T_{MI}$	0.7
Local Track File	800	$1/T_{ML}$	0.1
System Track File	20,000	$1/T_{MS}$	0.7
Bookkeeping for New File Entry			
Track Initiation File	150	S_R+N_F/T_S	2.7
Local Track File	150	S_R	0.2
System Track File	150	S_S	0.3
Tracker Selection	900	$N_A(N_S-N_T)/NT_S$	47.1
Message Transmission			
System Messages	150	$N_A(1/T_U+2/T_C+1/T_H)$	26.3
2-Address Messages	400	$3N_A N_T/NT_S$	8.6
1-Address Messages	300	$4N_A/NT_C+4FN_A(N_S-N_T)/NT_S$	31.8
Message Reception	200	Sum of Message Transmission Rates	60.6
		Subtotal	907.6 TIPS
Overhead (50%)			453.8
		Total	1.4 MIPS

TABLE 2.6

NEW PARAMETERS INVOLVED IN THE DATA PROCESSING REQUIREMENTS ANALYSIS

(Other Parameters are listed in Table 2.2 on page 43)

Symbol	Parameter	Value for Example
S_R	Rate at Which New Targets Enter the Surveillance Coverage of Each Radar	1 per s
S_S	Rate at Which New Targets Enter the Surveillance Coverage of the System	2 per s
T_{MI}	Maintenance Interval for Track Initiation File	3 s
T_{ML}	Maintenance Interval for Local Track File	10 s
T_{MS}	Maintenance Interval for System Track File	30 s
R_T	Transmission Repetition Frequency	1,000 per s

required data-processing rate in millions of instructions per second (MIPS). The instruction counts and the expressions for the repetition rates can be used to determine the data processing requirements for other sets of parameter values that might be of interest (in some cases the numbers of instructions for some operations also depend to some extent on certain parameters).

The data-processing execution rates for the example parameter values are summarized in Table 2.7 for the nine system configurations. The data-processing requirements for all of the configurations and modes of operation are in the 1-3 MIPS range. The lower values are obtained when there is both a Local Track File and a System Track File at each node (Configurations 1, 2, 6, and 7), with the higher values required when there is only one track file or none at each node (Configurations 3, 4, 5, and 8) with one exception (Configuration 9).

TABLE 2.7

SUMMARY OF DATA PROCESSING REQUIREMENTS

(Including an Additional 50% Instructions for Overhead Functions)

Configuration Number	Execution Rate in MIPS
1	1.1
2	1.4
3	2.2*
4	2.9
5	2.3*
6	1.0
7	1.3*
8	1.8*
9	1.2

*At Operations Facilities or STF nodes only.

The example values of the data-processing execution rates are plotted in Fig. 1.3 on page 21. It should be emphasized that the results of this data processing analysis are based on a series of assumptions and estimates, many of which are difficult to substantiate until the algorithms involved have been defined in detail and a method of implementation has been developed. Furthermore, the execution rates that were obtained are average values; under conditions where certain radars must track an unduly large share of the targets, or where the targets are bunched together making association more difficult, the peak data processing loads may be considerably higher. Also, the 50% data processing overhead included to account for the real-time operating system is an estimate that could vary considerably depending on the implementation. Nevertheless, the results indicate that the data processing requirements for a netted air surveillance and control system are indeed in a reasonable

and interesting range--neither so small as to be trivially attainable nor so large as to be practically unattainable, particularly in view of recent and projected advances in the state-of-the-art which provide increasing data processing capabilities with reduced hardware size and cost.

2.2 REAL-TIME DATA PROCESSING FUNCTIONS

The data-processing functions which must be performed in a tactical air surveillance and control system are described in Sec. 2 of Volume 2. Three primary functions critical to the successful operation of such systems--track initiation, track association (or correlation), and track filtering--are analyzed in detail. These descriptions and analyses are summarized in this section.

2.2.1 List of Real-Time Functions

Section 2.1 of Volume 2 lists and describes the data processing functions that must be performed as part of the operation of a network of automated radars. A summary of these functions is given in Table 2.8.

2.2.2 Track Initiation

The track-initiation process involves the association of measurements of target position and possibly velocity to determine whether or not the returns are from the same target and if so to obtain an estimate of the target position and velocity for track-filter initialization. Track initiation can be carried out using different types of measurements, numbers of measurements, and measurement spacings, with different levels of performance associated with each of the variations. Five track initiation algorithms were investigated; they are listed in Table 2.9.

<u>False-Alarm Track Initiations</u>. In any radar, false alarms due to noise will occur on occasion. Each of the five track-initiation algorithms

TABLE 2.8

REAL-TIME DATA PROCESSING FUNCTIONS

1. Local Track-While-Scan Functions

    Track Initiation

    Track Association (Correlation)

    Track Update

    Track File Maintenance

    Clutter Mapping

    Other Functions (e.g., manual intervention modes, local jammer response, IFF data processing)

2. Local Computer-Directed-Track Functions

    All functions in (1) above, plus

    Radar Scheduling

    Track Measurement Request Processing

    Scan Generation

    Null Return Processing

    Lost Track Processing

    Multiple Return Processing

3. System Track Functions

    System Track Initiation

    System Track Association

    System Track Update

    System Track File Maintenance

    Target Handover

    Jammer Response Coordination

    Automated Site Registration

4. Communications Functions

    Individual Message Processing (each message type)

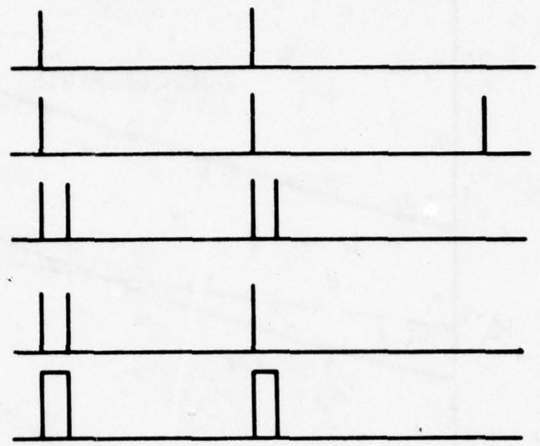
    Message Transmission

    Message Reception

TABLE 2.9

TRACK INITIATION ALGORITHMS CONSIDERED

1. Two Measurements
2. Three Measurements
3. Two Measurement Pairs
4. One Measurement Pair Plus One Out of Two Measurements
5. Two Pulse-Doppler Bursts



was analyzed to determine its resistance to initiating tracks on false alarms. For the purposes of this analysis, one hundred false alarms per scan were assumed to be uniformly distributed over the surveillance volume of the radars, as specified in the Statement of Work. The surveillance volume used in determining the false-alarm density is that of a 50-n mi-range radar (92.6 km) with coverage up to a maximum height of 50 kft (15.2 km) and a maximum elevation angle of 20 degrees (the results are fairly insensitive to maximum elevation angle). The false-alarm track-initiation rates were calculated for several sets of parameter values to show the sensitivity to these parameters. The maximum target velocities used are 1,300 and 650 m/s, and the maximum accelerations are 6g and 3g. The standard deviations of the radar measurement errors that were used are 100 m in the horizontal plane, 200 m in height, and 100 m/s in radial velocity.

As an example of the results obtained, the expected numbers of false-alarm track initiations are plotted in Fig. 2.4 as functions of the

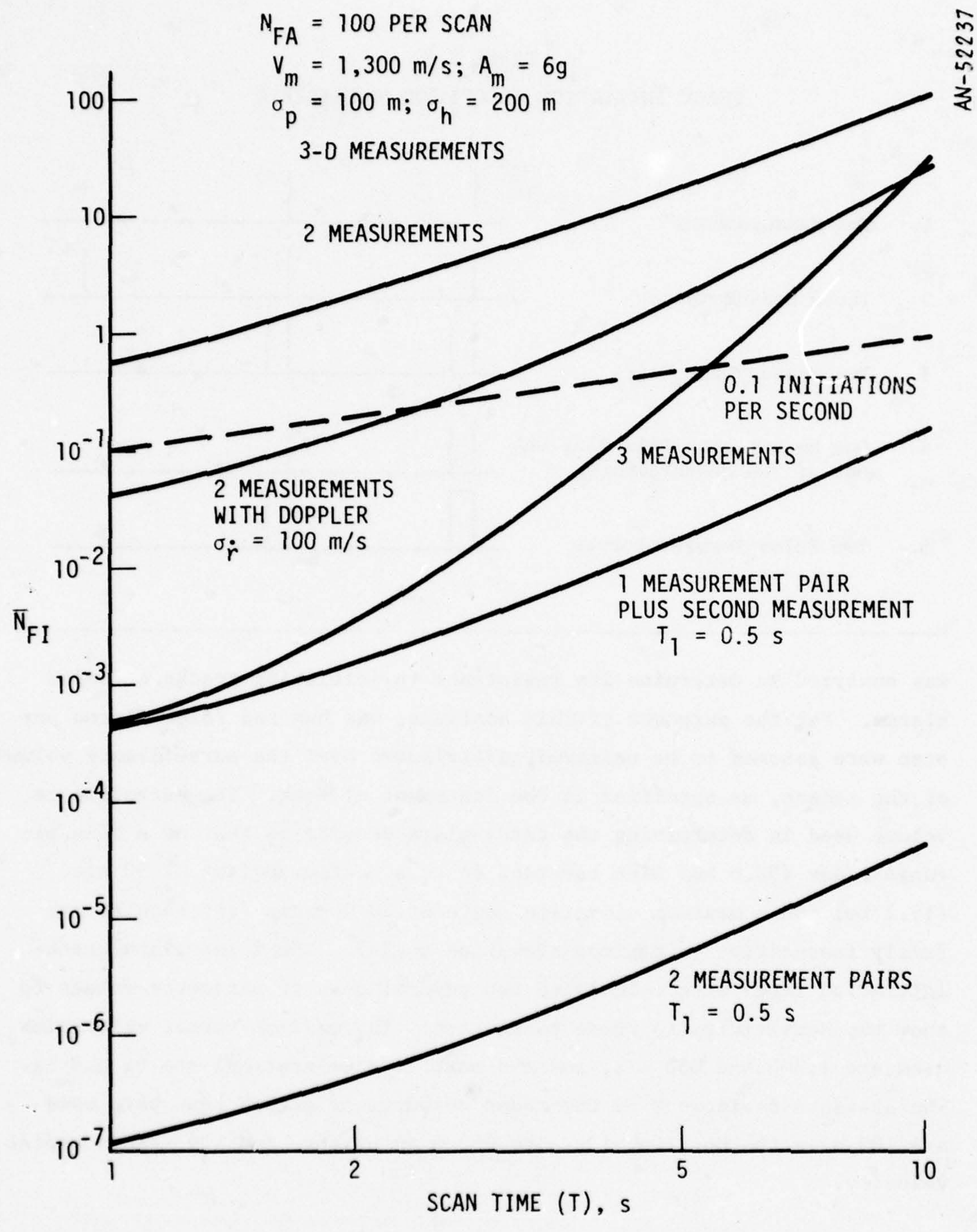


Figure 2.4. Expected Number of False-Alarm Track Initiations per Scan--Comparison of the Algorithms Considered

scan time or the time between measurements (or measurement pairs) for the five algorithms considered. These plots are for three-dimensional (or, in the Doppler-velocity case, four-dimensional) measurements with the parameter values listed in the figure. The results for two-dimensional measurements are significantly worse, as would be expected. The improvement in performance with increasing algorithm complexity and amount of information is obvious in Fig. 2.4.

To use these results in selecting a track-initiation algorithm and specifying suitable values of the radar parameter values (particularly the scan time), a tolerable level of false-alarm track initiations per scan (or per second) must be established. A detailed analysis of the consequences of track initiations on false alarms is required to establish such a specification, but the application of a simple criterion described in Vol. 2 suggests that the false-alarm initiation rate--the expected number of track initiations on false alarms per second--should not exceed 0.1. This threshold is plotted as the broken line in Fig. 2.4. The expected number of false-alarm initiations is seen to be above this threshold for all values of the scan time for the two-measurement algorithm, and for all but the shorter scan times with two Doppler measurements. The false-alarm-initiation rate is below this threshold for the three-measurement algorithm except for the longer scan times and for the measurement-pair-plus-one-measurement algorithm, and is well below this level with two pulse pairs.

Along with the false-alarm-initiation performance, another factor that should be considered in selecting a track-initiation algorithm and radar parameter values is the probability of successful initiation as affected by the radar probability of detection. For successful track initiation, each set of returns in the track-initiation sequence must be detected, i.e., must produce a signal which exceeds the detection threshold. Ideally, the probability of detection is close to unity, but in the environment of a tactical engagement the detection probability may be

degraded significantly. The probability of successful track initiation falls off rapidly as the probability of detection is reduced from unity. The more measurements that are required in the track initiation algorithm, the lower the probability that all of the measurements will be detected. Thus, for example, if the probability of detecting a single measurement is 0.9, the probability of detecting two measurements as required by Algorithm 1 is 0.81, but the probability of detecting four measurements as required by Algorithm 3 is only 0.66. Detection-probability considerations lead to the selection of the simplest algorithm (using the fewest measurements) for which the false-alarm track-initiation performance is adequate.

2.2.3 Track Association

The probability of correctly associating a radar return with the proper track depends on the magnitudes of the measurement error, the track prediction error, and the deviation of the target position from the predicted track due to maneuvers initiated since the last measurement, as well as on the association algorithm used and on the density of false alarms and other targets in the vicinity of the target of interest. The track-association investigation considered three association algorithms, the size and shape of the association volume, and the association performance as affected by false alarms and other nearby targets.

2.2.3.1 Association Algorithms

Closest-Pair. Probably the simplest association algorithm is to associate each radar return with the closest track within a specified association volume. More precisely, this algorithm consists of the following steps: (1) extrapolate each track of potential interest to the time of the radar measurement; (2) determine the distance from the measured target position to each of the predicted target positions which lie within a previously specified association volume; and (3) associate the radar measurement with the closest track.

Statistical Distance. A refinement of the closest-pair algorithm is to compute and use the so-called statistical distance between the measurement and the extrapolated state. The statistical distance is the actual distance normalized by the error covariance of this distance. This distance (squared) has a known probability distribution (chi-square) and the probability of a successful association can be computed for any given association threshold, assuming all of the errors are Gaussian.

Assignment Algorithm. When multiple measurements and tracks lie close enough together that they must be considered as a group for association, the distances between measurements and tracks that could be associated with the same target (those which lie within the potential-association volume with respect to one another) can be conveniently displayed and processed as elements of a two-dimensional matrix. While different measures of distance can be used, the square of the distance, or statistical-distance squared, which tend to weigh more heavily the larger measurement-track separations, appear to be reasonable measures for this application.

Once the distances have been evaluated, a reasonable and well-defined procedure for associating each measurement with a track is to determine the set of pairings which minimizes the sum of the squares of the distances. That is, as the solution of the association problem, choose that combination of measurements and tracks which minimizes Σd_{mi}^2, where d_{mi} is the distance from measurement m to track i and the summation is over M or I terms, whichever is less, and M and I are the numbers of measurements and tracks being considered. One term is selected from each row and column. This type of problem is known as the assignment problem in network flow theory, and efficient algorithms for its solution are known.

2.2.3.2 Association Volume

It is important to minimize the association volume in order to minimize the probability of making a false association. The factors which

affect the association volume in both size and shape include possible aircraft maneuvers, measurement errors, and model errors. Each of these was analyzed in detail as discussed in Volume 2; a summary follows.

Aircraft Acceleration Effects. If an aircraft being tracked initiates a maneuver after the last tracking measurement, any prediction of its future position will be in error by the extent of the deviation from its previous flight path that is introduced by the maneuver. To obtain an indication of the magnitude of this deviation, it was assumed that the aircraft undergoes a constant acceleration, either in a transverse or lateral direction perpendicular to its flight path or in a tangential or axial direction along its flight path or in both directions at once. The displacement of the aircraft from the position it would have had with no acceleration was calculated and plotted as a function of the time since the last measurement and the aircraft velocity and acceleration.

One example of the rapid increase in the growth of the association volume with time since the last measurement is shown in Fig. 1.5 on page 25, where the locus of possible target positions is plotted for a target velocity of 300 m/s and maximum lateral and axial accelerations of 10g and ± 2g. The effect of target velocity on the location and shape of the association volume is illustrated in Fig. 2.5, which shows the association volume contour[1] for a velocity of 1,000 m/s at a time of 5 seconds after the last measurement, along with a contour for 300 m/s, both for the same maximum accelerations. The two volumes are about the same size, but the curvature is considerably less at the higher target velocity.

Measurement Error Effects. Radar measurement errors also influence the size of the association volume. These errors enter in two ways: (1) through errors in the predicted target position caused by previous measurements, and (2) through the errors in the present measurement. The

[1] The association volume is a volume-of-revolution about the horizontal axis.

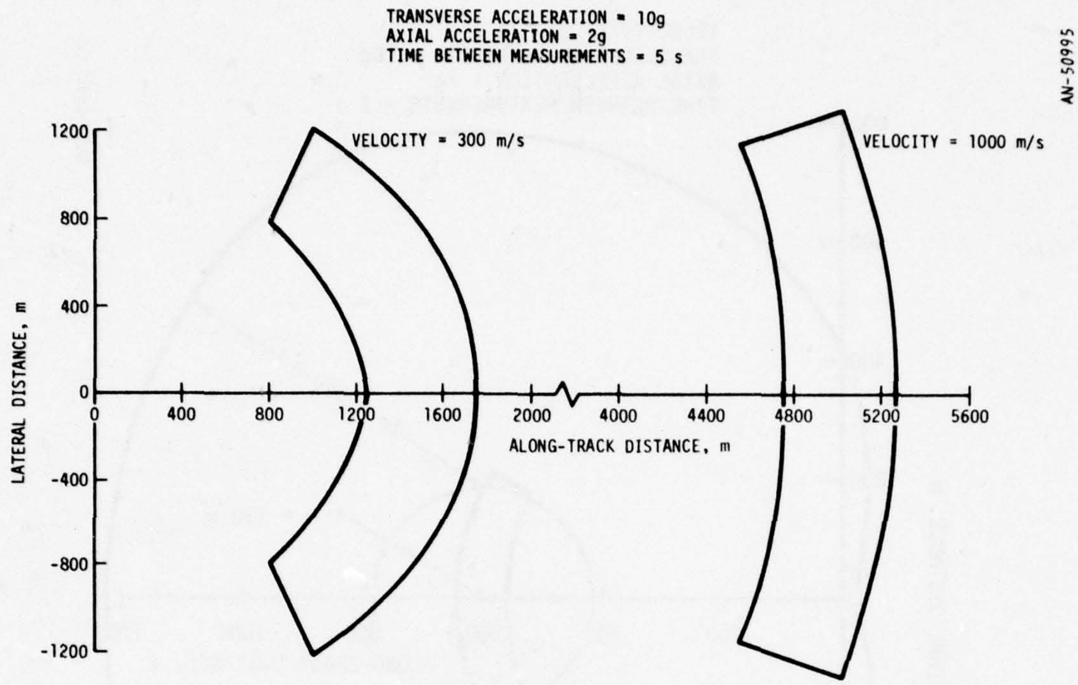


Figure 2.5. Projection of Association Volume Due to Possible Target Acceleration

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measurement and prediction errors of interest are random in nature and can only be described statistically. For this analysis the standard deviation (1-σ) in the measurement error was assumed to be 100 m, and the combined error of the distance between the measurement and the track was shown to be 190 m. The 3-σ value of the error (570 m) was used in defining the association value to ensure that a high percentage of measurements will lie within the correct association volume.

As an example, the combined effect of the target acceleration and the measurement error on the size and shape of the association volume is shown in Fig. 2.6. The acceleration-displacement contour for a velocity of 300 m/s, transverse and axial accelerations of 10g and 2g, and a prediction time of 2 seconds is shown along with a 1-σ circle 190 m in radius. The outer contour, which represents the boundary of the association volume for the parameter values used, is a 3-σ distance of

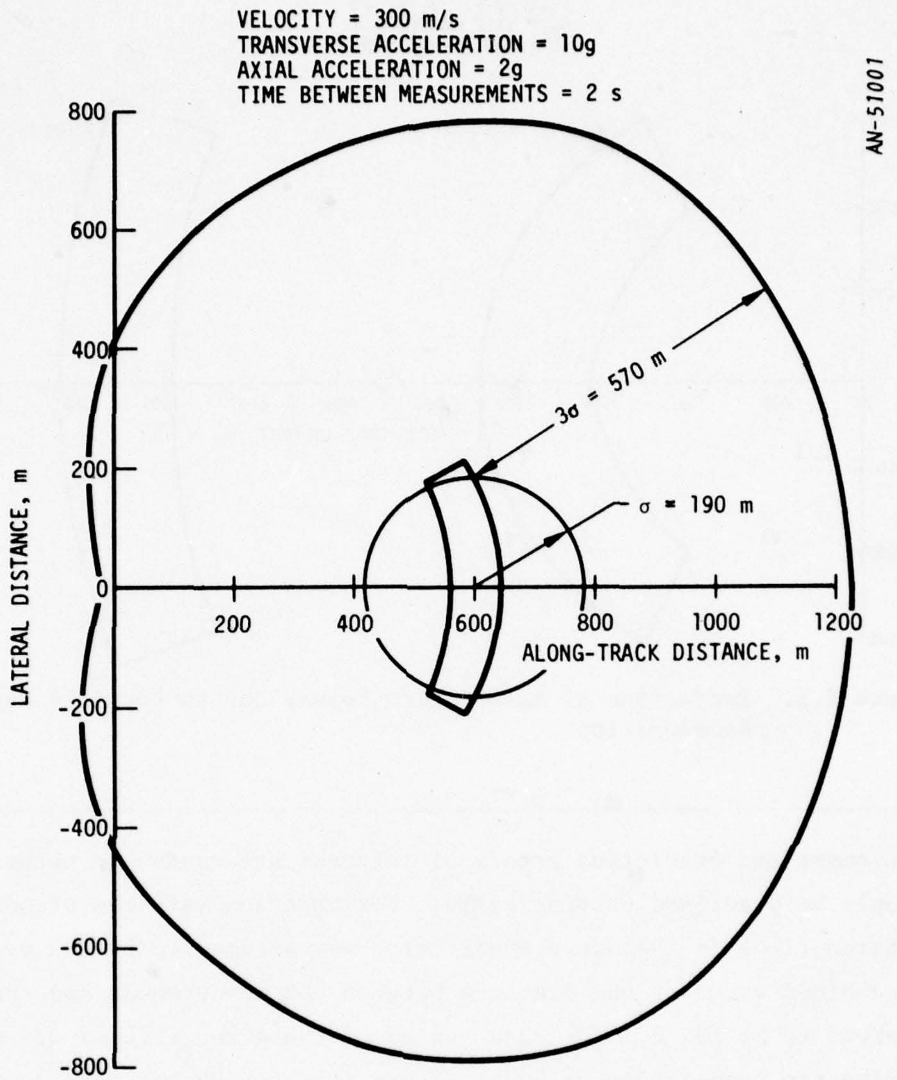

Figure 2.6. Association Volume for Track Association

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570 m from the closest point on the acceleration-displacement contour. Since the 3-σ distance here is considerably larger than the maximum displacement due to acceleration, this outer contour is roughly circular in shape and could be well approximated by a circle (or a sphere in three dimensions) in a practical implementation.

Similar contours are plotted in Fig. 2.7 for the same parameter values except for time between measurements and the extrapolation time, which is 5 seconds here. The association volume is larger in this case and departs significantly from a circular shape and is much more difficult to model in a computer.

Model Error Effects. A quadratic function (rather than the usual linear function) is a reasonable model of aircraft flight in the present

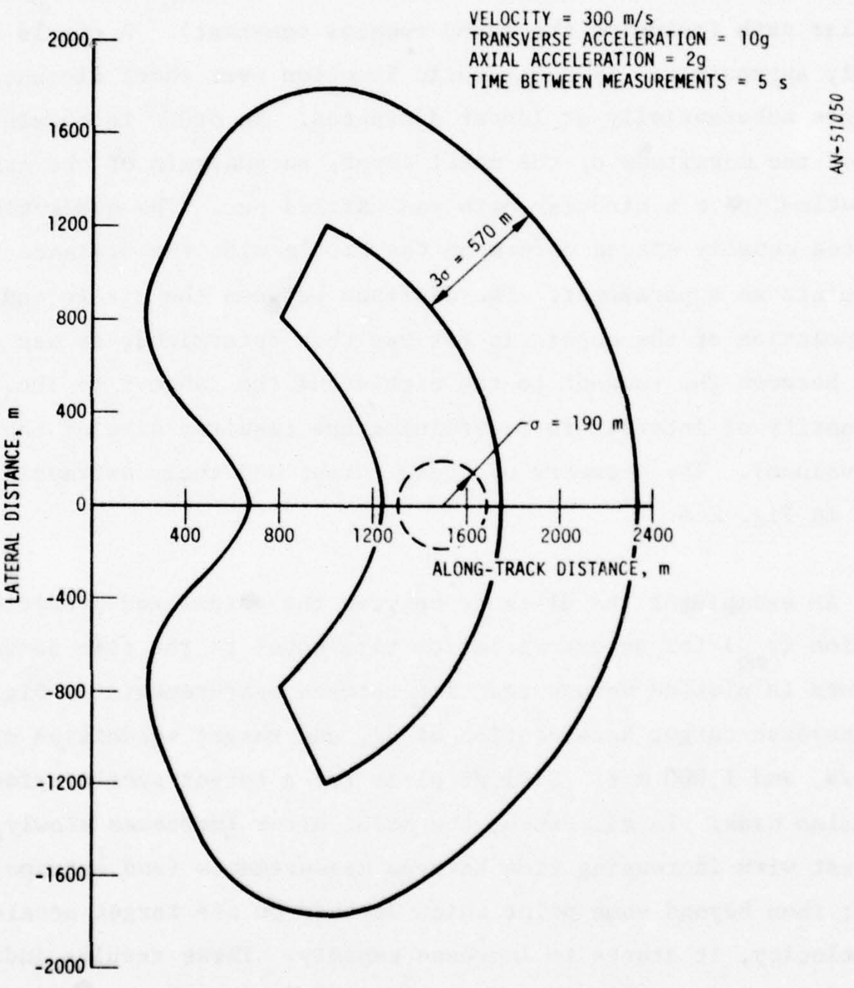

Figure 2.7. Association Volume for Track Association

air surveillance context where it is desirable to be able to extrapolate some time ahead without having to update the System Track. However, even when aircraft are performing constant-acceleration maneuvers, they do not follow flight paths that are quadratic functions, and predictions of their position based on the quadratic model are therefore in error. This model error is in addition to the errors due to target maneuvers and measurement noise which were discussed in the preceding paragraphs.

An aircraft performing a constant-acceleration maneuver follows a circular path (assuming the speed remains constant). A circle can be closely approximated by a quadratic function over short distances, but diverges substantially at longer distances. In order to obtain an indication of the magnitude of the model error, an analysis of the case of a quadratic-fit to a circular path was carried out. The quadratic was fitted to three equally spaced points on the circle with the distance between the points as a parameter. The distance between the circle and the extrapolation of the quadratic fit was then determined, as was the distance between the tangent to the circle and the tangent to the quadratic (a quantity of interest in determining the required size of the association volume). The geometry of these curves and their extrapolations is shown in Fig. 2.8.

An example of the distance between the actual and predicted target position (ε_{mq}) for an extrapolation time equal to the time between measurements is plotted versus the time between measurements in Fig. 2.9 for a transverse target acceleration of 3g, and target velocities of 100 m/s, 300 m/s, and 1,000 m/s. Similar plots for a target acceleration of 10g were also made. In all cases, the model error increases slowly from zero at first with increasing time between measurements (and extrapolation time); then beyond some point which depends on the target acceleration and velocity, it starts to increase rapidly. These results indicate that the model error can be a major contributor to the track-prediction error for high target accelerations.

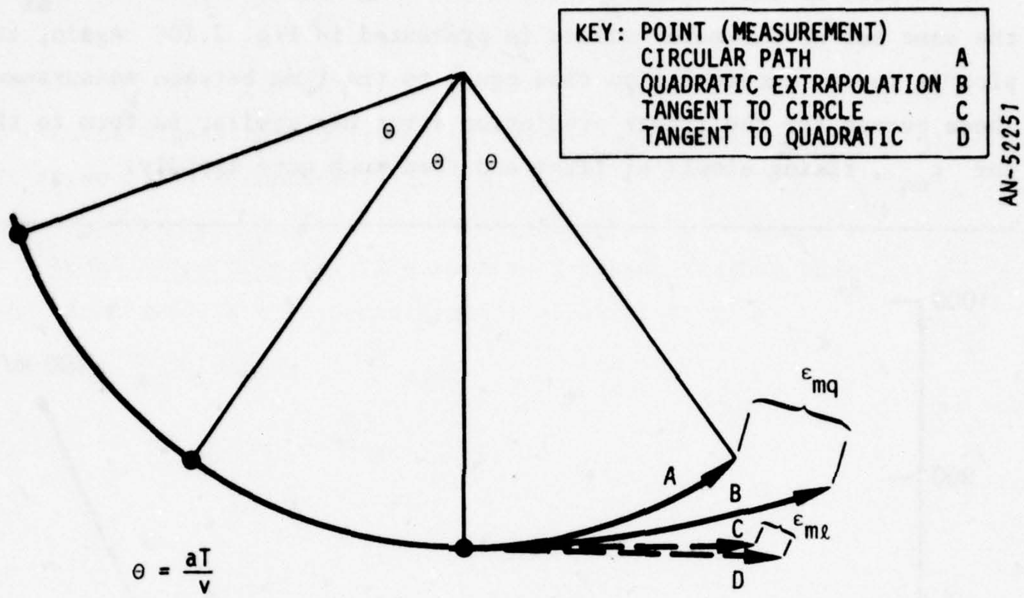

Figure 2.8. Quadratic Fit to Three Points on a Circular Path and the Extrapolation of These Curves and Their Tangents

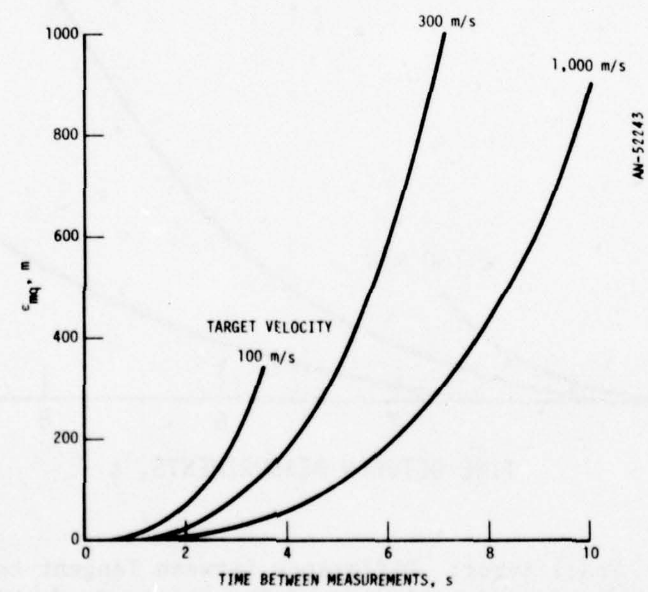

Figure 2.9. Model Error: Difference Between Constant 3g Acceleration Circle and Quadratic Prediction, One Sample Time Ahead

A plot of the distance between the tangents to the curves ($\varepsilon_{m\ell}$) for the same set of parameter values is presented in Fig. 2.10. Again, this plot is for an extrapolation time equal to the time between measurements. These curves for the linear prediction error are similar in form to those for ε_{mq}, rising slowly at first and then much more rapidly.

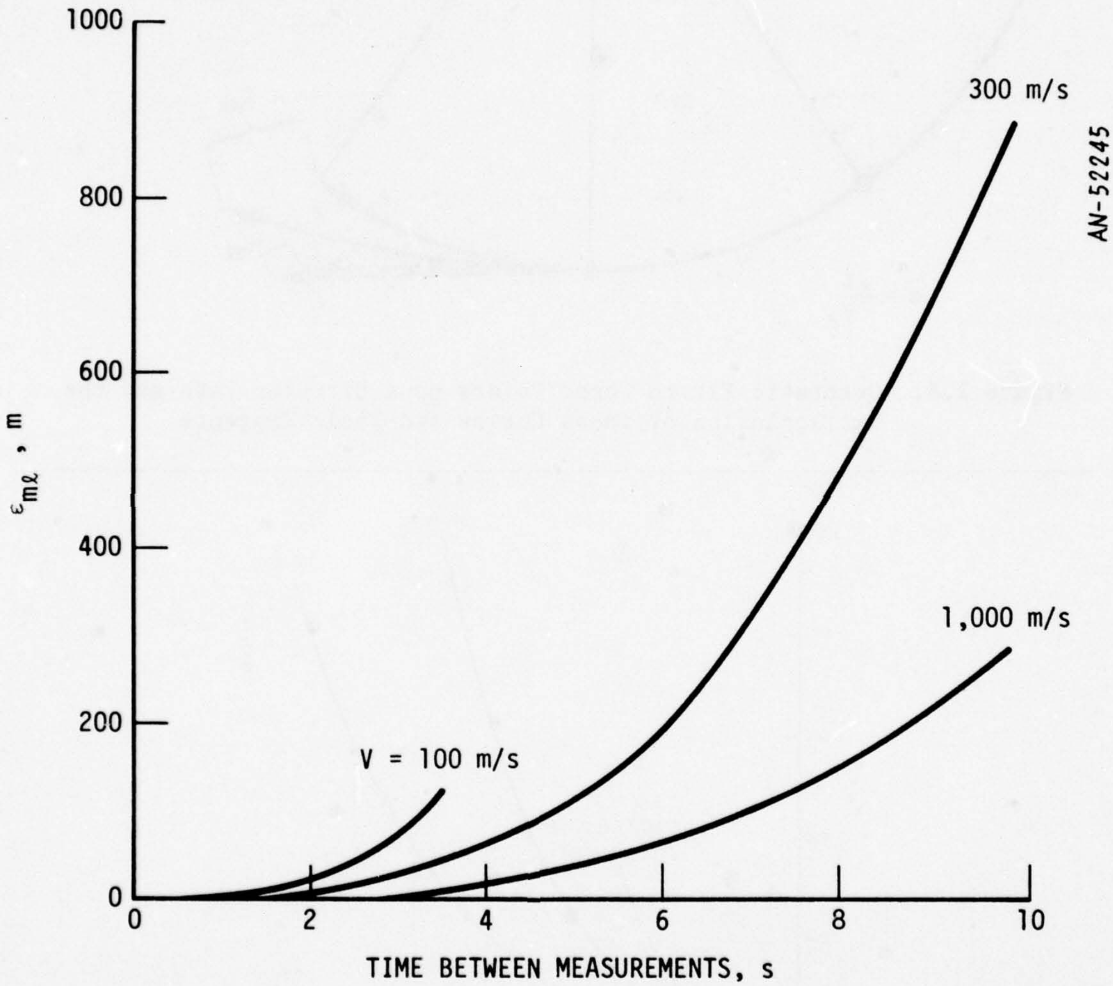

Figure 2.10. Model Error: Difference Between Tangent to Constant 3g Acceleration Circle and Tangent to Quadratic Prediction One Sample Time Ahead

2.2.3.3 Association Performance Analysis

To gain insight into the relationship between parameters describing the association performance and the radar and target parameters, the association process was analyzed using idealized models and considering special cases. First the analysis of the probability of associating a track with a false alarm is summarized, then the problem of incorrect association of closely spaced targets is discussed in terms of certain simple target geometries.

False Alarm Associations. If a false alarm occurs in a location close to a projected track, it may be associated with the track. The probability of a false-alarm association is the probability that the distance from the predicted target position to the false alarm location is less than the distance from the predicted target position to the measurement location. As an example of the results of the analysis of this problem, the expected number of false associations per target per scan is plotted in Fig. 2.11, as a function of the time between measurements

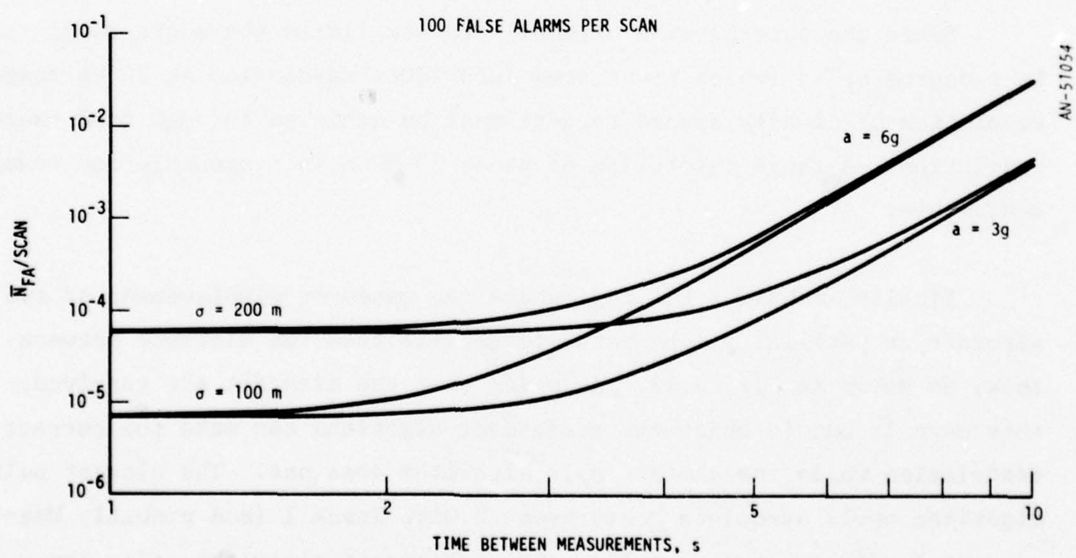

Figure 2.11. Expected Number of False-Alarm Associations per Target per Scan

(scan time). For 100 false alarms per scan, two values of aircraft maneuver (3g and 6g) and two of measurement error (σ = 100 m, 200 m). The curves are flat out to 3 or 4 seconds and then start to rise rapidly, indicating that the time between measurements should be less than about 3 seconds to hold the number of associations with false alarms to the minimum attainable level.

Multiple Target Associations. With many targets in track, it is possible to incorrectly associate a measurement from one target with the track on another target. A basic requirement for tracking closely spaced targets is that they must be resolved by the radars. If a radar can resolve two targets, it can measure their positions with an error that is at least an order of magnitude less than the distance between the targets. Thus, it should always be possible to correctly associate the measurements with the tracks for these targets unless they have performed a maneuver since the last measurement that has produced a displacement comparable to the distance between them. The latter possibility can only be prevented by having a sufficiently high measurement rate.

Since the antenna size of mobile radars limits the angle resolution to a degree or so (which translates into 500 m resolution at 30 km range), resolution of closely spaced targets must be achieved through good range resolution. A range resolution of about 20-50 m is reasonable and readily achievable.

Finally, consider the case where the maneuver displacement of two aircraft on parallel flight paths is greater than the distance between them, as shown in Fig. 2.12. Assuming that the aircraft are resolved, this case is one in which the assignment algorithm can make the correct association while the closest pair algorithm does not. The closest pair algorithm would associate Measurement 2 with Track 1 (and probably Measurement 1 with Track 1 as well). The assignment algorithm using the squares of the distances would properly associate the measurements and tracks, since

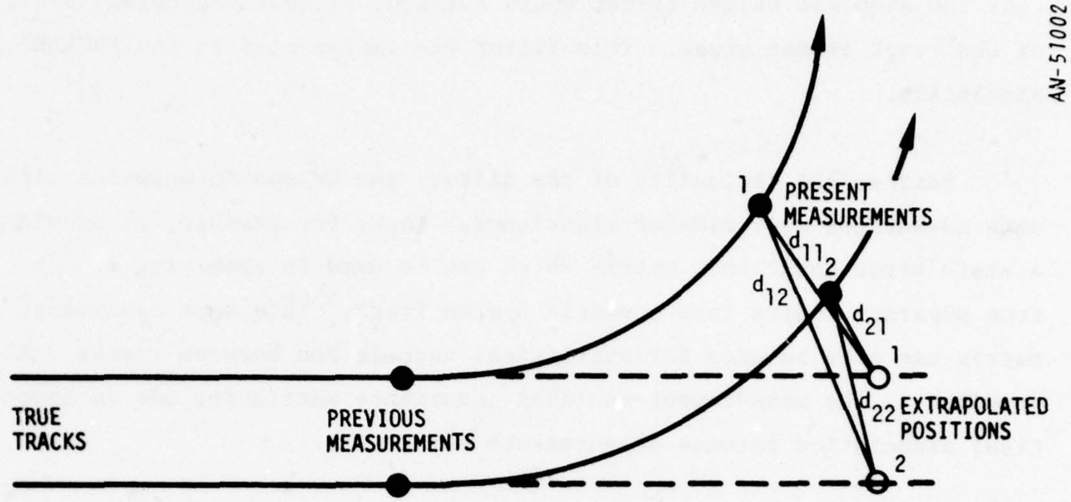

Figure 2.12. Maneuvering Targets Geometry

$$d_{11}^2 + d_{22}^2 < d_{12}^2 + d_{21}^2$$

Thus the association performance in this case depends in part on the algorithm that is used.

2.2.4 Track Filtering

The track filters considered during the study were the Kalman, the α-β, and a weighted-least-squares. These analyses are summarized next.

Kalman Filter. The Kalman filter is the optimal filter for linear systems perturbed by Gaussian noise for several reasonable optimization criteria such as minimum mean square error, maximum likelihood, and minimal variance Bayes' estimate. The extended Kalman filter has proven useful in many non-linear problems as well, and has been widely studied for use in tracking maneuvering aircraft. While several versions of the extended Kalman filter were considered during the study, it was decided

that the simplest Kalman filter would suffice, since the accuracy required of the track is not great. This filter was implemented in the TACRAN2 simulation.

Besides the optimality of the filter, the Kalman formulation offers some advantages over simpler algorithms. Thus, for example, it provides a state error covariance matrix which can be used in combining tracks from separate radars into a single System Track. This same covariance matrix can also be used for statistical association between tracks. Also provided is the measurement-residual covariance matrix for use in statistical association between measurements and tracks.

The disadvantages of the Kalman filter as compared with simpler filters are the increased data processing resources required to implement the algorithm and, more importantly in the present context, the higher communications bandwidth required to transmit the state error covariance matrix.

Many computer runs were made to determine the performance of the extended Kalman filter in the automated netted tactical air surveillance context. Maneuver (or model) noise, which is inserted into the filter to inform it that the linear flight model is incorrect, is an integral part of this type of filter, and runs were made to show the effect of different levels of this inserted noise. Figure 2.13 shows the horizontal-plane projection of the (distributed local) track on a 2,000-km/hr (556-m/s) aircraft for $\sigma_m = 4g$ of maneuver noise. The track begins with initiation by two measurements six seconds apart. Then other measurements are added approximately every two seconds. (The measurements were taken by three track-while-scan radars each with a six-second scan period, and the measurements were pooled to provide an average data interval of two seconds.) The track is sufficiently good that the symbols for the positions of the aircraft, the measurement, and track extrapolation are nearly on top of each other in the plot. A similar plot shows that there is no significant difference if the maneuver noise is increased to 8g.

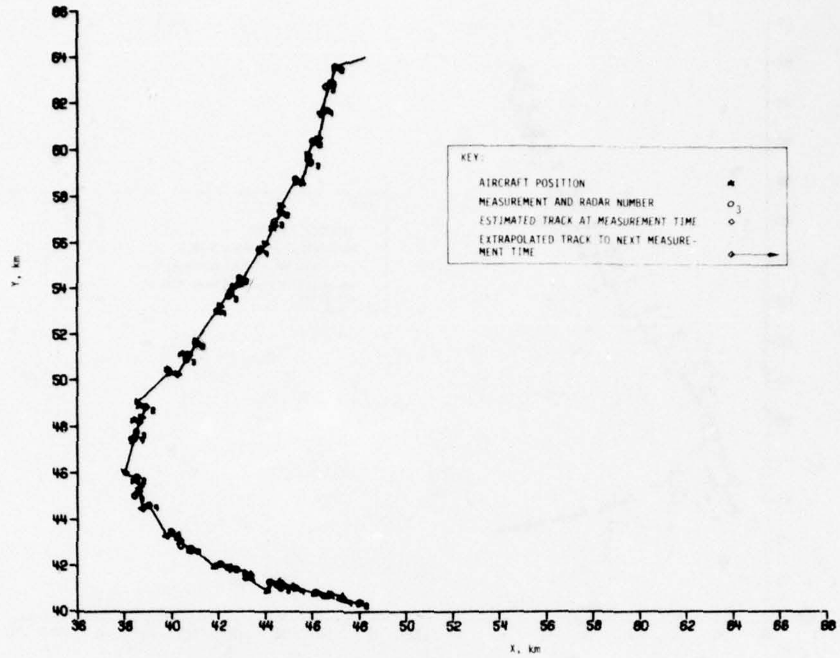

Figure 2.13. Kalman Filter Tracking With 4g Maneuver Noise

However, when no maneuver noise is inserted, the result is quite different. Figure 2.14 shows that the track is very poor in this case, and track would be lost if association was not forced to occur as it was during these runs. The reason for such poor behavior is that without maneuver noise the filter assumes that the straight-line model is perfect, and after several measurements begins to believe that its state estimate is much better than the measurement (i.e., the error covariance becomes small), and the measurements are nearly ignored.

It was concluded that the Kalman tracking filter tracks aircraft adequately as long as the maneuver noise is non-zero and is set to a reasonable value such as 4g. The complexity of the filter, however, is such that simpler filters are probably more desirable in the present application.

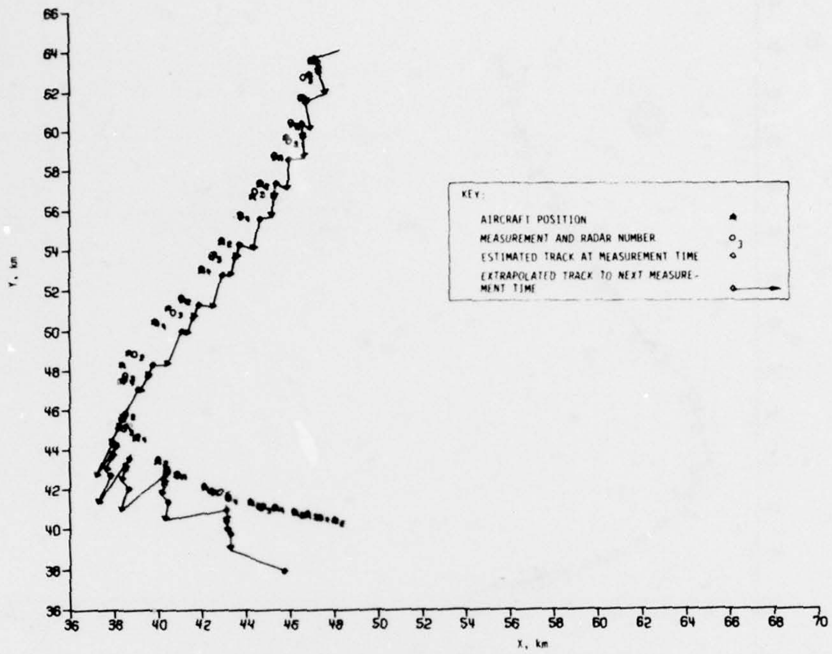

Figure 2.14. Kalman Filter Tracking With No Maneuver Noise

<u>α-β Filter</u>. The α-β filter is a greatly simplified recursive filter. None of the covariance equations associated with the Kalman filter need be calculated. The simplicity of the α-β filter has resulted in its widespread use and investigation. In the present study it was the first filter to be implemented in the TACRAN simulation. The simulation showed the performance of this filter to be satisfactory.

Adaptation to the presence of maneuvers is sometimes used with α-β filters. Maneuver detection can be based on the size of the measurement residual (the difference between the measured position and the extrapolated track). If the aircraft is flying along a straight path, the past measurements that went into the extrapolated position are still valid and can be weighted heavily in the filter. If a maneuver is detected, the present measurement should be weighted more heavily.

α-β-γ Filter. The α-β-γ filter is an extension of the α-β filter for the case where the state includes acceleration position as well as velocity. It was not investigated during the study, but may have merit in the netted surveillance concept. The advantage in carrying along acceleration is that the resulting track can follow more types of aircraft paths than just a straight line. This in turn may permit less frequent updating of the System Track.

Weighted Least-Squares Filter. The least-squares filter fits a curve to the last N points so as to minimize the sum of the squares of the distance between the points and the curve. This filter is attractive for tracking targets where, due to maneuvers only, the last few points are likely to be on the present trajectory. In the weighted least-squares filter, each measurement is weighted by the signal-to-noise ratio.

In order to reduce the System-Track update frequency, a fit to a quadratic curve (rather than a linear curve) is used in the TACRAN3 simulation. (Higher derivatives are believed to be too noise to use effectively.) Figure 2.15 shows one of a series of TACRAN3 runs that were made to see how well the least-squares filter tracks a very highly maneuvering target. The aircraft trajectory includes two 9g turns; the aircraft velocity is 1,000 km/hr (280 m/s). The least-squares filter used five measurements spaced two seconds apart. The track is noisy as expected, but not unreasonably so considering the large maneuvers. The largest association distance (the distance between the measurement and the extrapolated track) is about 600 m. Other runs were made using different measurement noise samples, different numbers of measurements (3 and 7) and a different measurement spacing (one second). It was found that three measurements are insufficient (the largest association distance is over 900 meters), while seven points gives results similar to five points (600 m association distance). Doubling the measurement rate, as expected, improves the track considerably; with a one-second measurement spacing the largest association distance is approximately 300 m.

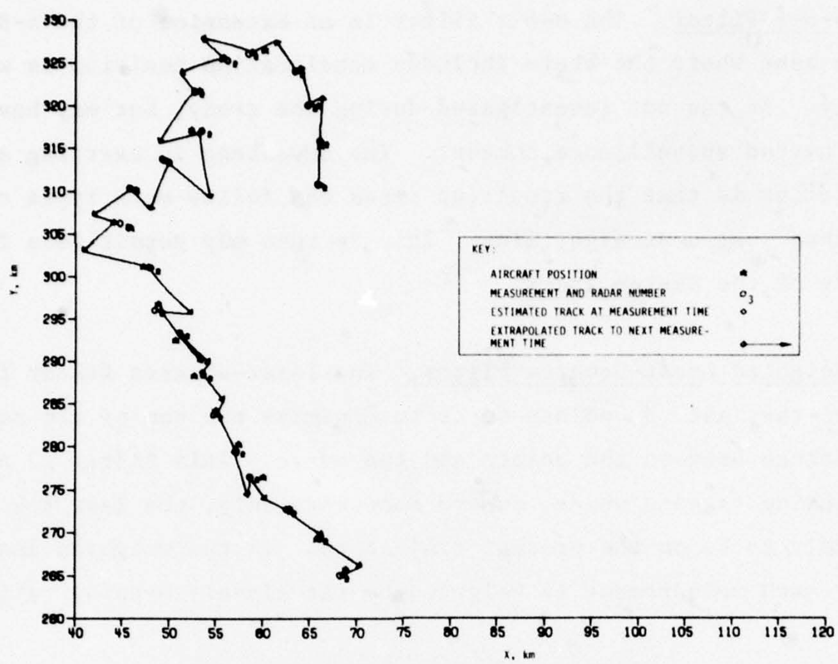

Figure 2.15. Track With 5 Points, 2-Second Measurement Interval (Case 1)

Tracking Errors. The effect of measurement errors on quadratic extrapolation was analyzed. The variance σ_x^2 in the extrapolated position due to measurement noise is shown in Fig. 2.16 for the case where the standard deviation σ_n is the same for each measurement (and therefore the weights are also the same for each measurement). These results show that the extrapolation error due to noise increases rapidly with time when small numbers of points (N) are used. For example, for $N = 4$, the extrapolated position error is nearly ten times the measurement error when the position is extrapolated only three sample periods ahead.

2.3 DISTRIBUTED NETWORK SIMULATION

Section 3 of Volume 2 describes in detail the distributed network simulation that was constructed during the study. Three versions of the simulation, called TACRAN (Tactical Air Control Radar Net), were constructed. TACRAN1 and TACRAN2 simulate different versions of system alternative Configuration 1 and TACRAN3 simulates Configuration 2.

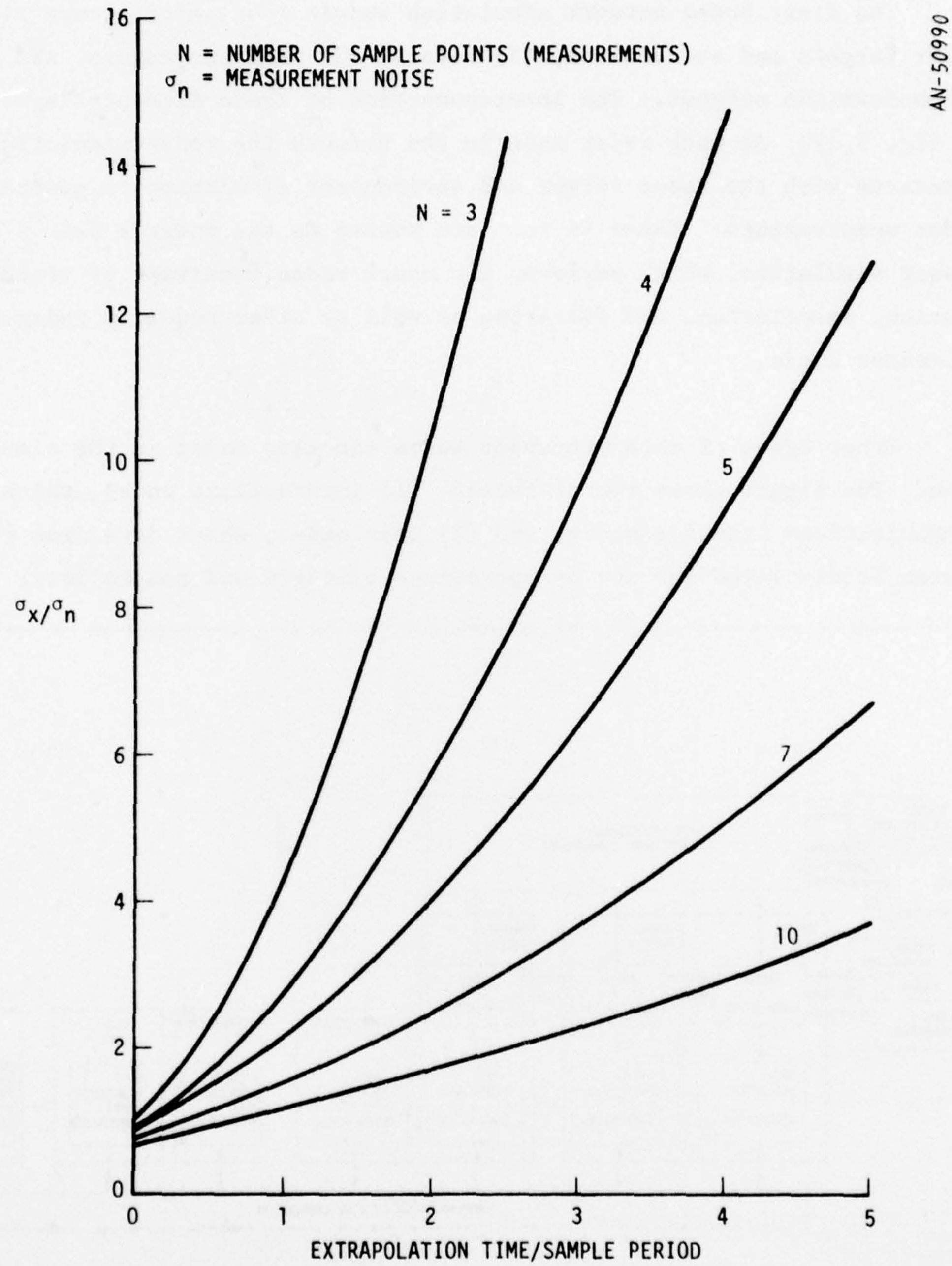

Figure 2.16. Extrapolation Error Due to Measurement Error for Least-Squares Fit to Second-Degree Polynomial

2.3.1 Overview

The distributed network simulation models four major elements: (1) radar targets and environment, (2) radars, (3) data processors, and (4) communications network. The interconnection of these elements is shown in Fig. 2.17. At each radar node in the network the radar simulation interacts with the radar target and environment simulation to generate radar measurements. These in turn are passed to the radar's data processor simulation, which performs the usual radar functions of track initiation, association, and filtering as well as other required radar data processor logic.

Other types of data processor nodes can also exist in the simulation. The figure shows two of these: (1) intermediate nodes, which are communications transfer nodes, and (2) user nodes, where data from the system is displayed for use by operations planners and controllers.

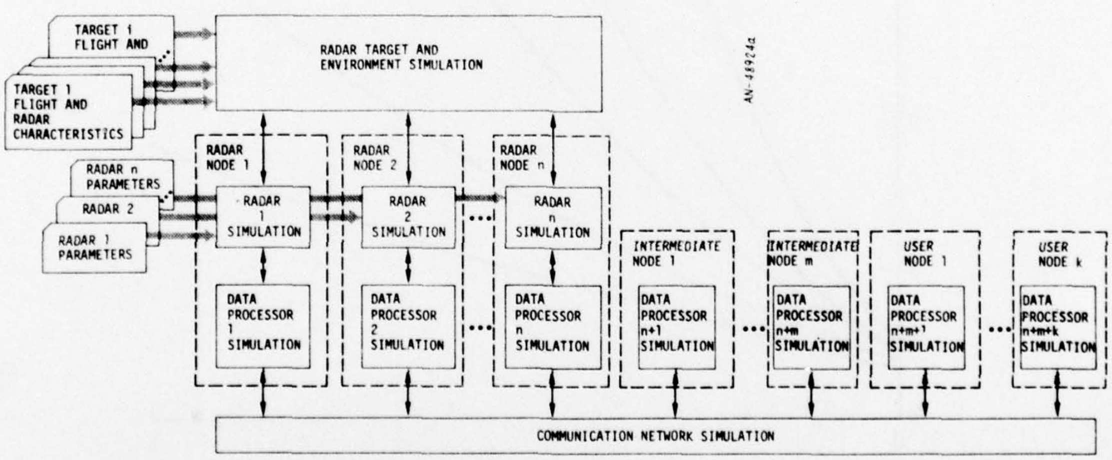

Figure 2.17. Distributed Network Simulation

All data processors are interconnected through the communications network simulation, which permits complete flexibility of the interconnection.

The Distributed Network Simulation is completely modular to facilitate interchange of simulation models. Any number of radar types, data processor types, radar target types and communication system types can be simultaneously modeled. Each type can be replicated as often as required using the same code module. Since dynamic storage allocation with overflow to secondary storage is used throughout, there are no upper limits to the numbers of targets, radars, data processors, communications messages, etc., that can be simulated. (There may, however, be some practical limits in terms of computer running time and cost.)

2.3.2 TACRAN Simulation Models

Radar Simulation Model. The TACRAN simulation models track-while-scan radars, providing noisy radar returns in up to four dimensions (range, azimuth, elevation, and Doppler). The radar simulation is entered separately for each radar in the net. Each time it is entered all aircraft returns and false alarms are generated for the next scan sector. (The size of the sector is defined as an input; typically about a 20-degree sector has been used.) The simulation system passes the returns to the radar data processor in the proper order at the proper time.

Aircraft Flight Simulation Model. Aircraft are defined by their mass, area, drag, thrust, and maximum accelerations. Flight paths are described by an initial state and a few points along the path. Each point defines a desired position and speed. The actual flight path is determined by proportional navigation on the next point. As an aircraft nears a point, it begins flying towards the point beyond it; thus aircraft do not necessarily fly precisely through the points.

Communications Simulation. The communications simulation interconnects all of the data processors in the network by point-to-point communications. The interfaces between the data processor simulations and the

communications simulations are realistic; that is, a sending data processor sets up a message to one or more other data processors and turns it over to the communications simulation, which in turn routes the message over the appropriate communication links with appropriate queuing and delays, and delivers it to the receiving data processor.

Data Processor Simulations. The data processing is not simulated in the same sense as the other major models. Rather, the actual data processing logic and algorithms that might be used in the real system are coded in a high level language. As such, the data processor simulation can be considered a breadboard or brassboard model of the real-time data processing subsystem.

2.3.3 Simple-Algorithm System (TACRAN1)

The first version of the simulation, TACRAN1, was a simple configuration whose primary purposes were to gain initial insight into the type of systems being simulated. Each radar/data processor node has both a System Track File and a Local Track File. All track initiation, association and update operations are performed using the Local Track File, which is different at each node. Maneuver detection is used to determine when to update the System Track File, which is replicated (to the degree possible) at each node.

2.3.4 Kalman-Filter System (TACRAN2)

The TACRAN2 version of the simulation was developed as a sequel to TACRAN1. The basic system concept is the same, but the track association and update algorithms are much more sophisticated. Associations are performed with chi-square tests, and updating is by Kalman filtering.

2.3.5 Pooled-Data System (TACRAN3)

Both of the first two versions of TACRAN had conceptual and algorithm problems that were uncovered while using the simulations. Therefore

another system construct was developed to overcome these deficiencies, which included poor association probability due to the low scan rate and large communication and data processing loads. In this new construct, which is simulated in TACRAN3, the data from several radars is pooled to effectively increase the tracking rate on each aircraft, association is performed using a more sophisticated algorithm (the assignment algorithm), and the tracking filter uses a weighted least-squares quadratic fit to the last few pooled measurements.

As an example of the results from the TACRAN3 simulation, Fig. 2.18 shows the geometry for a test run. Four nodes were selected to represent all the node types: Radars 1, 2, and 3 can see the three aircraft targets, Radar 4 is representative of a node that cannot see the aircraft (the maximum 80 km ranges are indicated on the figure). Radars 1 and 3 see targets during only part of their flight paths; they operate at long

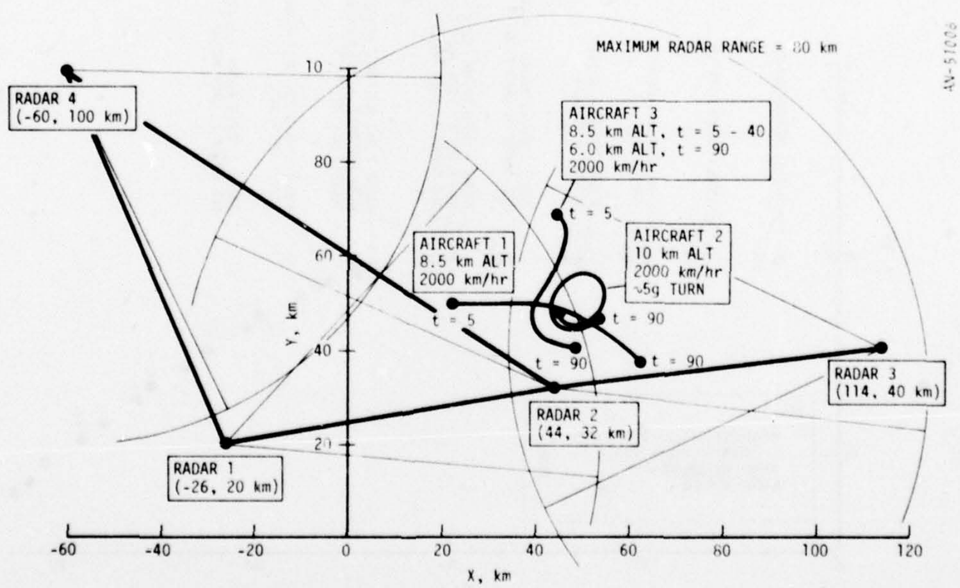

Figure 2.18. Geometry for TACRAN3 Test Run 1

range with low signal-to-noise ratio. The communications paths (shown in heavy lines) were chosen to represent an "interesting" network. The radar scan period is 6 seconds.

The history of the Distributed Local Track (DLT) on Aircraft 1 is shown in Fig. 2.19 for a run that was made using an unweighted least-squares filter. The tracker selection logic operates as expected with one exception: Radar 1 asks for help on its fourth measurement. Radar 3 correctly notes this and adds itself as a tracker and drops Radar 1. Next, however, Radar 1 decides (based on a very noisy range-rate calculation) that it does not need help and that it has a better reception time than Radar 2, so it adds itself as a tracker and drops Radar 2. This points up a common threshold problem, and shows that to prevent this kind of "thrashing," a double-threshold system may be needed.

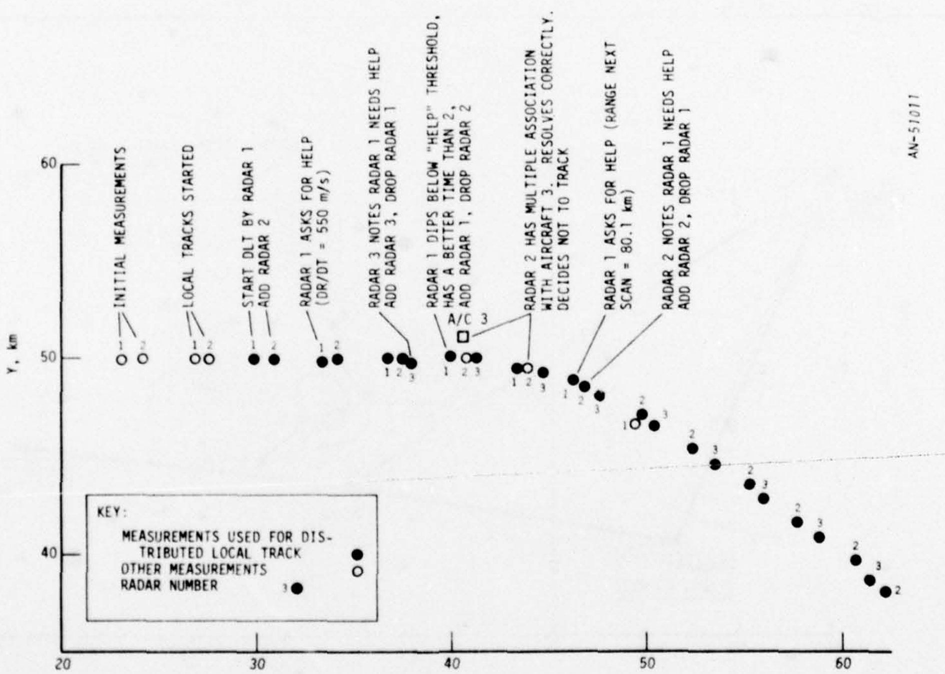

Figure 2.19. Distributed Local Track History, Aircraft 1

A set of runs was made to investigate the performance of weighted least squares tracking filters and to test the tracker-selection logic. In Fig. 2.20, which shows a portion of the Distributed Local Track on Aircraft 3, the weighting is equal to the signal-to-noise ratio of the measurement, which is nearly the optimal weighting. The corresponding System Track is shown in Fig. 2.21. The System Track is updated when it deviates from the DLT by more than 1 km. Such a criterion leads to infrequent updating with sharp discontinuities. A display of the past history of this track might be confusing with its discontinuities. However, a display of an aircraft's present estimated position and velocity vector, which may be all that is needed, should not be confusing, even with occasional discontinuities.

2.3.6 Simulation System Details

The TACRAN simulation was constructed using a number of simulation systems and tools developed and refined at GRC during the past ten years.

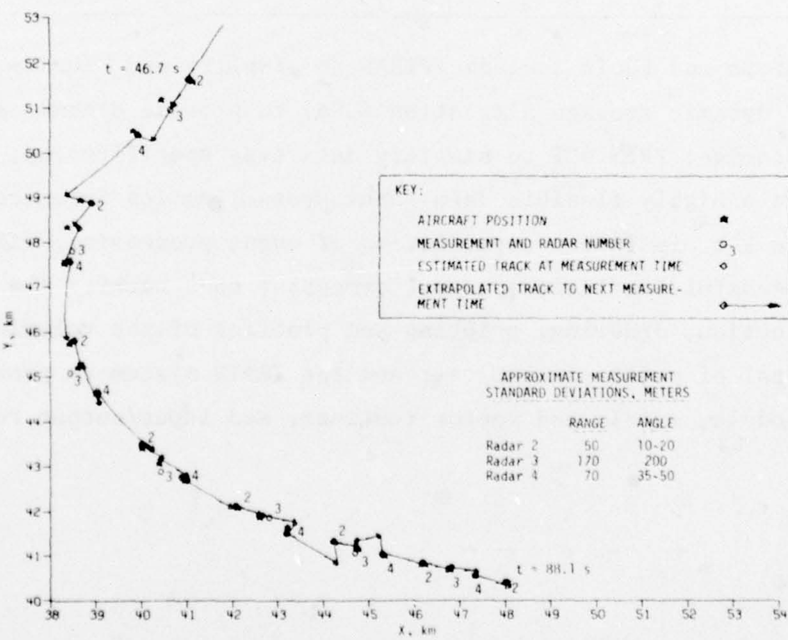

Figure 2.20. Distributed Local Track Performance for Aircraft No. 3

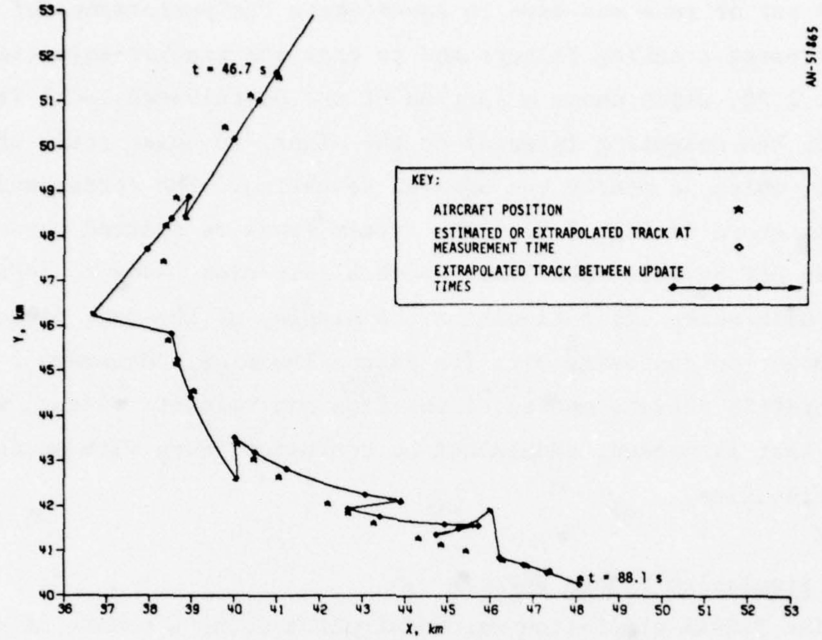

Figure 2.21. System Track Performance for Aircraft No. 3

These systems and tools include IFTRAN to simplify and clarify code preparation; dynamic storage allocation (DSA) to provide dynamic assignment of data storage; PRINTOUT to simplify data type specification; FLEXREAD, to provide a highly flexible data input system; Action Sequence Chains to provide the simulation capabilities of event processing, time delays and other useful facilities; a post processor that permits the assimilation, selection, ordering, printing and plotting of the voluminous output data typical of major simulations; and the TRAID system to provide trajectory models, matrix and vector routines, and input/output routines.